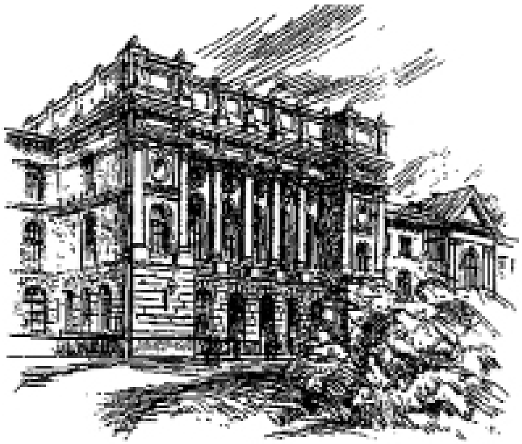
МИНИСТЕРСТВО НАУКИ И ВЫСШЕГО ОБРАЗОВАНИЯ РОССИЙСКОЙ ФЕДЕРАЦИИ



НАУЧНО-ТЕХНИЧЕСКИЕ ВЕДОМОСТИ САНКТ-ПЕТЕРБУРГСКОГО ГОСУДАРСТВЕННОГО ПОЛИТЕХНИЧЕСКОГО УНИВЕРСИТЕТА

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НАУЧНО-ТЕХНИЧЕСКИЕ ВЕДОМОСТИ САНКТ-ПЕТЕРБУРГСКОГО ГОСУДАРСТВЕННОГО ПОЛИТЕХНИЧЕСКОГО УНИВЕРСИТЕТА. ЭКОНОМИЧЕСКИЕ НАУКИ

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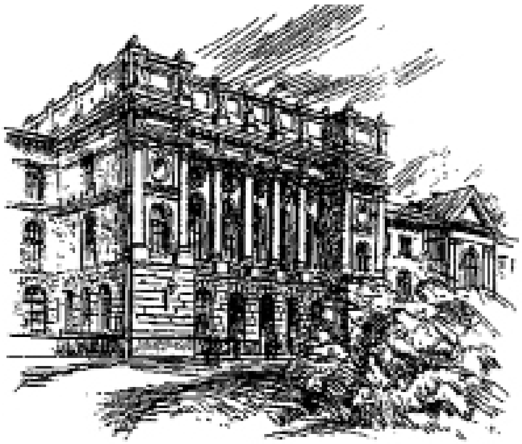

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STRATEGIZING OF ECONOMIC SYSTEMS DIGITAL TRANSFORMATION: A DRIVER ON INNOVATIVE DEVELOPMENT

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The main directions of the regional economy advanced development include the stimulation of small and medium business, import substitution policy, improvement of the professional qualities of the economically active population, and development of a favorable environment in the interaction of business and government. However, in modern conditions, a new driver of economic growth is needed: the digital transformation. For successful transformations, resulting in a significant increase of efficiency, clearly defined goals and business objectives are required, i.e., the available strategy, implementation of which is realized in the need to achieve a specific state of the economic system, in which its development is ensured through synchronization with national, regional and sectoral priorities. Moreover, along with the preparedness to strategizing, an appropriate external environment is essential, presuming the capabilities of the regional economic system to support innovation. The article presents the authors' approach to the problems of analyzing the processes underlying the regional economy. A purposely designed toolkit consisting of economic and mathematical models, databases, and applied software is aimed to intensify the framework of studying the regional economy development management. The example of the socio-economic system of St. Petersburg enabled to carry out a comprehensive assessment of the consistency of the regional economy in the formation of a favorable business environment for economic entities at the initial stage of digital transformation. The result of the study is the substantiation of the provisions that to reduce the risks of stagnation in economic growth, support of the leading regional enterprises is essential, which act as the leaders of progress, introducing capital-intensive technologies, and conducting digital business transformation. Availability of such poles of growth reduces the barrier in terms of accessing digital technologies for small and medium businesses, thereby ensuring the sustainability and competitiveness of the region as a whole. The paper made it clear that the key to the successful digital transformation is the creation of IT ecosystems that implement the concept of a systematic approach to decision-making in business management, applying knowledge economy technologies, such as predictive analytics, artificial intelligence, big data, cloud computing, etc. Recommendations for the generating of unified information space in the concept of a digital enterprise are provided.

Keywords: information system, planning, forecasting, regional economy, development strategy, change management, digital platform, digital transformation, digital twin

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СТРАТЕГИРОВАНИЕ ЦИФРОВОЙ ТРАНСФОРМАЦИИ ЭКОНОМИЧЕСКИХ СИСТЕМ КАК ДРАЙВЕР ИННОВАЦИОННОГО РАЗВИТИЯ

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В качестве основных направлений опережающего развития региональной экономики выделяются стимулирование малого и среднего предпринимательства, политика импортозамещения, повышение профессиональных качеств активной части занятых граждан, формирование благоприятного окружения при взаимодействии бизнеса и власти. Однако в современных условиях необходим новый драйвер экономического роста, которым является цифровая трансформация. Для успешного проведения преобразований, результатом которых является существенное повышение эффективности, необходимы четко сформулированная цель и бизнес-задачи, то есть наличие стратегии, смысл реализации которой состоит в необходимости достижения такого состояния экономической системы, при котором ее развитие будет обеспечиваться через синхронизацию с общегосударственными, региональными и отраслевыми приоритетными целями. При этом, кроме готовности самого объекта стратегирования, необходимо наличие соответствующего внешнего окружения, то есть возможностей региональной экономической системы по поддержке инноваций. В статье представлен авторский подход к решению задач анализа процессов, составляющих основу региональной экономики. Разработан соответствующий инструментарий (экономико-математическая модель, база данных и прикладное программное обеспечение), усиливающий аппарат исследования проблем управления развитием региональной экономики. На примере социально-экономической системы Санкт-Петербурга проведена комплексная оценка состоятельности экономики региона по формированию благоприятного бизнес-окружения для хозяйствующих субъектов, находящихся на начальном этапе цифровой трансформации. Результатом исследования является обоснование положений, что для снижения рисков стагнации экономического роста, необходима поддержка ведущих региональных предприятий – лидеров прогресса, внедряющих капиталоемкие технологии и проводящих цифровую трансформацию бизнеса. Наличие подобных полюсов роста позволит снизить барьер доступа к цифровым технологиям для малого и среднего бизнеса, обеспечив тем самым устойчивость и конкурентоспособность региона в целом. Показано, что залогом успешности проведения цифровой трансформации является создание ИТ-экосистем, реализующих концепцию системного подхода к принятию решений по управлению бизнесом, используя для этого технологии экономики знаний, такие как предиктивная аналитика, искусственный интеллект, большие данные, облачные вычисления и пр. Даны практические рекомендации по формированию единого информационного пространства в концепции цифрового предприятия.

Ключевые слова: информационная система, планирование, прогнозирование, региональная экономика, стратегия развития, управление преобразованиями, цифровая платформа, цифровая трансформация, цифровой двойник

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Introduction

The global economy has recently been undergoing significant structural changes, resulting in a gradual abandonment of technologies, involving unskilled labor and high operating costs, to support production and business processes (management, logistics, sales, warehousing, maintenance). The emphasis is on capital-intensive production fit to operate almost automatically and focused on the production with high added value by minimizing operating costs. The reason for this is the drastic growth of so-called high technologies based on digital data processing (collection, analysis, modeling, forecasting, process control, etc.) and the possibility of obtaining energy from renewable sources (green power industry) [1]. New means of payment, such as cryptocurrency, are emerging along with different types and methods of communication embedded in production processes. Taken together, this leads to the need to revise the existing industrial and social relations, develop new strategies and actualize the features of socio-economic development, ensuring sustainable economic growth [2]. Moreover, considering the peculiarities of the Russian economy, these tasks should be solved mainly at the regional level since the federal level deals with global goal-setting (national projects), legal regulation (favorable business environment), general management, and control over the fulfillment of social obligations. The subjects of the Russian Federation fully participating in economic, business, political, and financial relations are meant to be the flagships of the national economy. Those regions with historically the most favorable conditions, obtaining sufficient raw material and human resources potential, should act as innovators, that is, to guide new technologies that have been tested in leading regional enterprises and recognized suitable for scaling and replication. This condition is essential to equalize the socio-economic situation in the regions and to ensure equal conditions and quality of life for citizens, regardless of their place of residence.

The implementation of the announced approach leads to the need for a radical restructuring (digital transformation) of technological processes and principles of management of large industrial enterprises, being the drivers of economic growth and the basis for the development of small and medium businesses. Digital transformation for enterprises striving both to maintain their positions in the market and to create a background for long-term development means:

1. A growth pole that ensures business diversification by stimulating the creation of new products, facilities, and services through digital technologies, possessing the adaptive and integration capabilities significantly higher than traditional ones [3].

2. The possibility of obtaining added value by optimizing business processes at all levels, reducing non-productive costs, increasing labor productivity, and extensively use the digital competencies of personnel [4].

3. Early arrangement of conditions for gaining access and conflict-free implementation of emerging new and complementary technologies [5, 6].

The list of national specialists whose work is devoted to assessing the level of socio-economic development and the region's readiness for transformations, studying the conditions and limitations of digital transformation, includes the names of such researchers as M.Yu. Arkhipova [7], L.G. Matveeva [8], I.V. Mitrofanova [9], A.A. Urasova [10], and others. Statements about the need to identify and take into account the set of influencing and stimulating factors in the formation of strategies and rules of behavior in competitive markets of economic entities are found in V.V. Akberdina [11], E.V. Balatsky [12], G.V. Korovin [13]. The basic principles underlined by new economic categories, such as the informational capacity of employment of the population, digital competencies of personnel, workplace information components that determine the strategy formation approaches to the involvement of the population in the digital economy, are stated by I.V. Novikova [14].

It should be noted that to achieve a complete process of digital transformation, well-defined tasks and business objectives are required. This presumes an available strategy, the implementation purpose of which is to ensure the enterprise development in synchronization with national, regional, and sectoral priority goals. Therefore, before planning and implementing any digital transformation projects, it is essential first to make sure that the enterprise itself is ready to uptake innovations and its environment also meets the stated goals and objectives.

Purpose

All of the above enabled defining the *goal of this study*: the development of theoretical and methodological provisions for strategizing the digital transformation of economic systems that determine their propensity for transformation and form the priority directions of advanced development.

Achievement of this goal provides for the solution of the following tasks:

– analysis of modern scientific literature on the subject of research;

– development of a conceptual model of the digital twin of the regional economic system with the institutionalization of indices (measurable indicators) that objectively reflect the state of its economic processes;

– assessment of readiness of the regional economy to create a favorable business environment for enterprises at the stage of digital transformation and preparing standard recommendations for them on developing an IT architecture to be the background of business management in a digital economy.

The object of the research is the socio-economic system of the constituent entity of the Russian Federation. *The subject of the research* is the processes of strategizing the digital transformation of economic systems.

The study is carried out on the example of St. Petersburg, which is of great strategic importance for the industrial and innovative development of both the Northwestern Federal District, in particular, and the Russian Federation as a whole.

Methodology

The relevance of studying the problems associated with the digitalization of the economy and its impact on the growth of social welfare, the importance of developing the theoretical and methodological foundations of change management, the role and significance of process innovations are noted by Russian (L.M. Borshch [15], T.V. Kramin [16], N.M. Rumyantsev [17], A.I. Tatarkin [18]) and foreign authors (J. Fagerberg [19], D. Kucera [20], R. Pradhan [21]). Concerning the development of strategic directions for the advanced development of socio-economic systems, the empirical basis of this study is the work of V.L. Kvint, who summarized the rules of strategic thinking and founded the Russian scientific school of theory of strategy, methodology, and strategizing practice. The basic postulate of the modern theory of strategy states that the availability of strategy is not really as important as its support with the relevant resources in all priority areas (development plants) [22].

The study of the works of these researchers leads to the conclusion that the readiness of the regional economy for transformation is determined by the consistency of the underlying systemic economic processes (development of transport and telecommunications infrastructure; the level of social support for the population; the number and quality of the economically active population; regulatory and legal support for business, the ability of enterprises to perceive innovations, etc.), and most importantly, the presence of a strategy presuming logically arranged and justified activities, synchronized in time and available resources. This postulate is a principle for all program documents, from the regional development strategy to the micro-enterprise strategy.

According to the world [23, 24] and domestic [25, 26] practice, for the formation of a strategy adequate to the goals and objectives of digital transformation, special tools are required that can identify and propose challenging schemes of advanced development for the need of accelerated digitalization of the economy. Such a toolkit may include an intelligent software package (strategist's office), the functionality of which would be sufficient to build a model (digital twin) of the region, considering its institutional, resource, social, technological, and other conditions. With the help of such a digital twin, by conducting experiments on it, mechanisms for triggering economic growth can be determined and justified for each specific regional economic system.

A regional economic system, like any other complex object, consists of a certain set of interacting processes, each of which can be formalized employing a mathematical function (fi) (Fig. 1). The set of local functions fi is the digital twin (F) of the system under study.

Input data are resources (factors x_i), the transformation of which in the process of implementation leads to a change in the target state of the regional economic system (an increase in the share of innovative products in GRP, in the number of jobs, in value added, etc.). The change in the target state is monitored through the corresponding indicators y_i.

Parametric analysis of *X* and *Y* dependencies enables the formation of relationships between factor (*X*) and indicator (*Y*), reflecting the nature of the studied processes. By feeding the set values X_i to the input of the digital twin, the predicted results Y_i can be obtained at the output. When the parameters of the “digital twin” change, there is an opportunity to set goals and predict the course of a certain economic process, thus the strategizing is implemented.

The regional economic system can be generally characterized by several systemic economic processes; institutionalization allows identifying measurable development goals of the constituent entity of the Russian Federation and establish the relationship between controlled factors[1] and indicators[2] (Table 1).

Table 1. List and characteristics of systemic economic processes that form the basis of the region’s economy

Economic process	Brief summary
1. Institutional environment	– determines the quality of work of the public administration institutions system, represented by the effective formation of the gross regional product
2. Basic education, Healthcare, Social protection	– evaluates the effectiveness of education management, quality, and comfort of the life of the population as the basis of its professional, labor, and reproductive potential
3. Transport infrastructure	– reflects the quality of spatial planning and the achieved logistic connectivity of the region as an effective system for the transfer of goods, works, production forces, and services
4. Microeconomic environment consistency	– characterizes the features of the current state of the region’s economy in terms of budget balance, reflects the financial potential of the regional government, guarantees the provision of state and municipal services, and, in general, forms the image characteristics of the region, the business climate, and attractiveness for business
5. Labor market efficiency	– distinguishes the attractiveness of labor activity in the region and assesses its potential as a center of attraction for qualified labor resources
6. Financial market	– reflects the nature of consumer behavior of the active part of the population according to its focus and ability to good independent investment development
7. Higher education and advanced training	– reflects the region’s ability to create high-tech industries and attract qualified labor resources
8. Technological development	– determines the readiness of the economy for the innovations conversion, the modernization of existing technologies, and the introduction of new ones, that is, the readiness of subjects of economic activity to realize commercial, organizational, personnel, production, technical, and innovative potentials
9. Interregional trade	– characterizes the region’s capability to increase and scale up sales and consumption markets by increasing labor productivity
10. Innovative capacity	– reflects the region’s ability to create and commercialize new technologies and industries, expand the range of products, goods and services

Source: Authors

To describe the mathematical dependence, a paired linear approximation of the dependence of indicators (*Y*) on controllable factors (*X*) was used with an additive consideration of the random component. Economic analysis of processes is carried out using multi-composition “factor-indicator” couples, where factor (*X*) is an indicator directly controlled by regional authorities, and indicator (*Y*) shows mainly the macroeconomic quality and the process dynamics, such as growth or decline in labor productivity in the region, the dynamics of the gross regional product, or the budget income index [27].

The constructed model of the regional economic system allows differentiating the possibilities of economic growth by the contributions of the individual processes into the total value, identifying and tracking both long-term and short-term changes. In practice, the modeling processes are implemented using spe-

[1] A factor is a controllable parameter, the change of which leads to the achievement of the strategic goals of the region.

[2] An indicator is a resulting parameter that reflects changes in the economic process due to a change in the related factor.

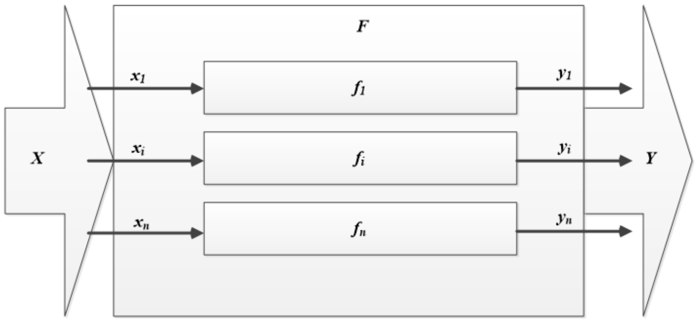

Fig. 1. Model of the regional economic system
Source: Authors

cial software "Forecasting and analytical system for strategizing the socio-economic development of the subjects of the Russian Federation" [28].

Results

Calculations proved the correctness of the processes proposed for describing the regional economic system, based on the official data of the Federal State Statistics Service for 2007–2019 (see Table 1). To determine the consistency of the economic processes under consideration, an algorithm was used to assess the list of threshold values of the main standard indicators of correlation and regression analysis, which characterizes the accuracy and statistical validity of the applied approximations of the "factor-indicator" dependence. The calculation results for St. Petersburg are presented in Table 2.

In general, a comprehensive analysis of all processes that make up the basis of the socio-economic system of St. Petersburg (Fig. 2) leads to a conclusion about its orderly and systematic development, the capability to provide a favorable business climate for those business entities that plan to start the digital business transformation.

The calculations prove that the overwhelming number of processes that make up the basis of the economy of St. Petersburg is ahead of the average level of similar processes development in the constituent entities of the Russian Federation included in the North-West Federal District.

This state of affairs testifies to the extremely high degree of readiness of the regional economic entities to start mastering the existing innovative development potential (in particular, the process "Technological development" is 39% ahead of the average level in the federal district, the process "Innovative capacity" is 141%, and "Transport infrastructure" is 34% respectively). At the same time, such state of affairs obviously has a downside, since, with an unfavorable development of the situation (economic crisis and/or worsening of the epidemiological situation), the macroeconomic indicators of the region may tend to decrease due to changes in consumer preferences, the outflow of qualified personnel and a decrease in investment necessary to support the continuity of innovatization.

To reduce the mentioned risks, regional technological enterprises in a crisis and post-crisis situation should become the conductors of digital technologies for small and medium businesses which experience certain difficulties in acquiring and mastering innovations, also because of their high initial cost threshold. In other words, leading regional enterprises must take on the leadership of introducing and testing digital technologies, going through all stages of digital transformation, and thereby preparing a bridgehead in the region for large-scale digitalization of the economy. They should become an example and technologies contributor for supporting small and medium-sized enterprises, which can significantly increase their efficiency by reducing transaction costs and introducing modern technologies and management methods. It

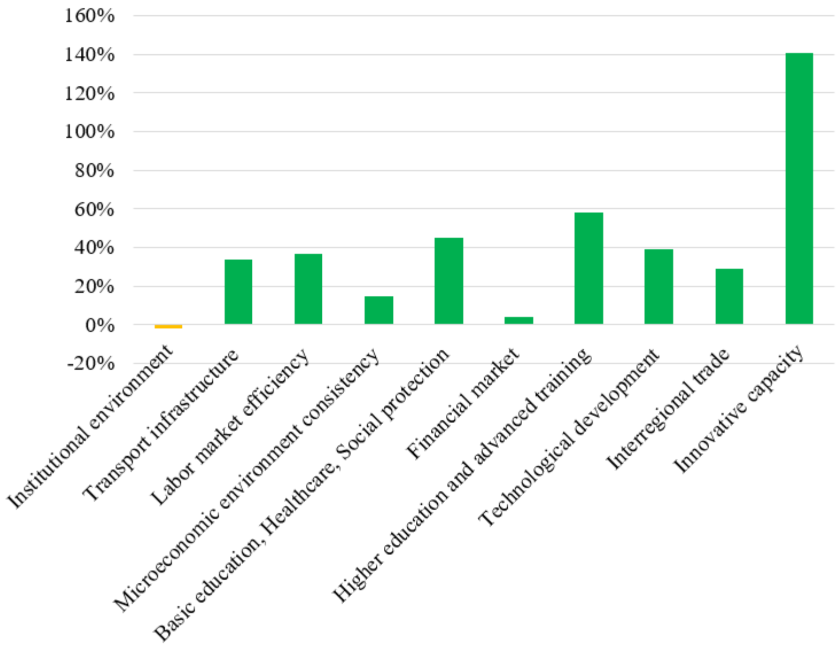

Fig. 2. Development indices of system processes in St. Petersburg relative to the average level of the constituent entities of the Russian Federation included in the North-West Federal District

Source: Authors

is necessary to start small, applying the available positive experience of digital transformation, using proven methods and technologies [29].

Among processes that are the most indicative and specifying the state and capabilities of the regional economic system of St. Petersburg, speaking about the implementation of professional competencies of the active part of the population regarding their applications for the sustainable advanced development of the territory, "Higher education and advanced training" and "Innovative capacity" are selected. These processes are decisive in terms of the formation and motivation of citizens capable of perceiving innovations and acquiring additional (digital) competencies necessary for the implementation of digital transformation procedures for both industrial and social relations.

1. "Higher education and advanced training"

Factor *X* is the share of spending on technological innovation, determined by the ratio of annual expenditures on technological innovations to the annual volume of investments in the capital stock. Factor management is formed by the need to attract a highly qualified workforce for the development of new jobs required from certain digital competencies.

Indicator *Y* means the number of employed people with higher education per 10 employees.

The process under consideration, along with the "Labor market efficiency", represents a kind of employment adjustment.

The estimated parameters of the process are shown in Fig. 3.

Analysis of the diagram from Fig. 2 demonstrates that the end of 2019 in St. Petersburg was marked by a significant increase in the share of technological innovation spending (for example, by 20% in comparison to 2017). At the same time, there was a decline in the number of employed personnel with higher education by 2.5% (out of 10 employees). This situation suggests that enterprises producing innovative goods and services experienced a decrease in operating costs and an increase in added value (a significant role belonged to the competence of employees and labor productivity). This indicates that the situation is under control despite the depreciation of the ruble, and the import substitution program is being successfully implemented.

Table 2. Data on the assessment of the consistency of economic processes that simulate the socio-economic system of St. Petersburg

Economic process	Factor, *X*	Indicator, *Y*	Correlation coefficient, R_{xy}	Approximation error, E_r
Basic economic processes				
Institutional environment	Regional Public administration Cost Index	GRP formation efficiency index	0.77	2.61
Basic education, Healthcare, Social protection	Regional budget spending index for the social block	Standard index of gross regional product	0.72	4.08
Transport infrastructure	Density of public hard surface road	Standard index of gross regional product	0.56	2.10
Microeconomic environment consistency	Regional budget gross spending index	Regional budget gross income index	0.97	3.14
Labor market efficiency	Index of regional budget expenditures on the national economy	Average wage index	0.73	3.37
Financial market	Share of regional budget expenditures under the national economy item	Credit exposure index of employed individuals	0.80	14.20
Economic processes of advanced development				
Higher education and advanced training	Share of spending on technological innovations	Number of employees with higher education per 10 employees	0.72	3.14
Technological development	Share of costs for information and communication technologies in total investment into capital stock	The ratio of the produced GRP to the volume of total (annual) investments into capital stock	0.86	8.02
Interregional trade	Foreign trade turnover index	Average annual foreign exchange labor productivity index	0.90	6.17
Innovative capacity	Technological innovations cost index	The share of innovative products, works, services	0.96	15.24

2. “Innovative capacity”

Factor X is the cost index for technological innovation, which is the ratio of the cost of technological innovation to the average annual number of employed citizens, modified to the average annual US dollar exchange rate. Factor *X* characterizes the investment activity of all regional economic entities in terms of implementation of technological innovations, directly or indirectly stimulated by the regional authorities. Indicator *Y* shows the share of goods, works, and services produced in % of the total volume of goods shipped, works performed, services rendered in the region for a calendar year.

The process under consideration, along with “Technological development”, is significant in terms of the formation of structural shifts in the economy, which determine the opportunities and capabilities of the overwhelming majority of economic entities for digital transformation.

The estimated parameters of the process are shown in Fig. 4.

Model visualization confirms that considered economic processes in St. Petersburg are valid from the viewpoint of the correctness of the formalization of the indices used to describe them. If necessary, to further analyze the influence of the components of factor *X* on the result of process *Y*, indicators can be detailed to develop the most appropriate management decisions (activities).

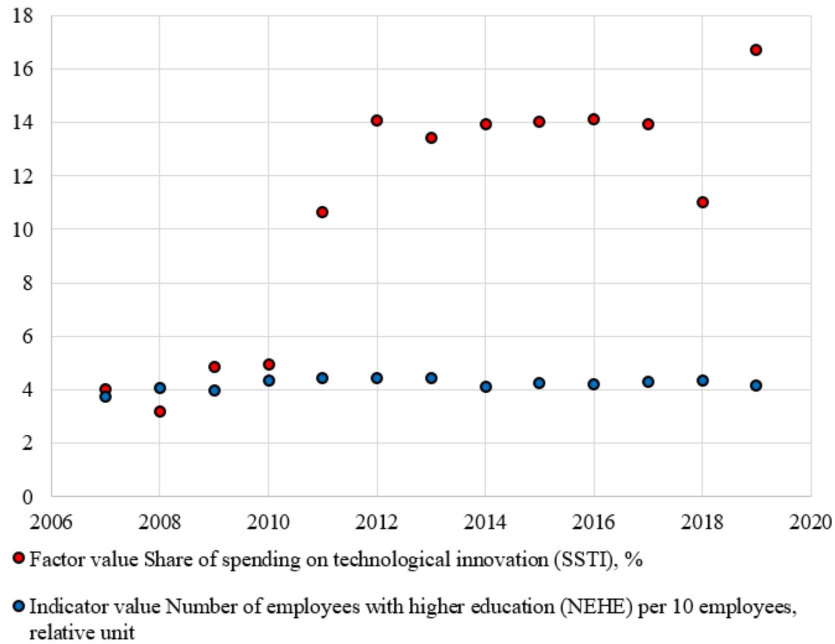

Fig. 3. Change in the controlled factor *X* and the resulting indicator *Y* in the period under review from 2007 to 2019
Source: Authors

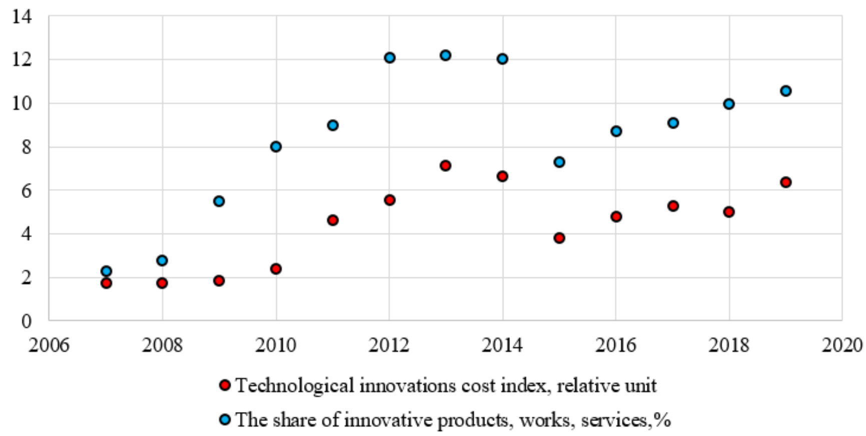

Fig. 4. Change in the controlled factor *X* and the resulting indicator *Y* in the period under review from 2007 to 2019
Source: Authors

In general, the results obtained are consistent with the main directions of the advanced development of the city, enshrined in a regulatory document – the Strategy of Social and Economic Development of St. Petersburg up to 2035, approved by the Law No. 771-164 of St. Petersburg dated December 19, 2018 (as amended on November 26, 2020), which defines goals and priorities, as well as formed indicators characterizing the degree of their achievement. The main factors that ensure the innovation of the region are: stimulation of the production of high-tech products and services, the growth of investment in human capital, and the digital transformation of the economy. Development based on the principles of digitalization of the economy is recognized as decisive in all spheres of socio-economic activity, increasing competitiveness and ensuring progressive economic growth.

Nevertheless, using the methodological approaches proposed in this article for a retrospective assessment of the macroeconomic state of the city of St. Petersburg allows a more reasonable proposition of a system of priority long-term targets. Although assessment of the quality of the current strategy is not the purpose of this study, based on the results of an extended and detailed analysis, certain recommendations can be issued on goal-setting and clarification of the priority directions of the city's development.

Discussion

One of the practical recommendations, useful for enterprises in the real sector of the economy planning to carry out the digital business transformation, is the creation of a digital IT ecosystem (digital platform), which performs the key function in successful transformations. Working with a digital platform is a recognized trend at the current stage of engineering, technology, and industrial and economic relations development. It seems that all business processes of the production life cycle, without exception, should be implemented using digital data and digital infrastructure in a unified information space (Fig. 5).

A technologically unified information space of an enterprise can be defined as a set of integrated applications that comprehensively support all the main business processes of operating and commercial activities, accounting procedures, customer relationship management, planning and forecasting, budgeting, management of regulatory and reference information, and also provide data exchange between all services.

The connecting link of the applications is the corporate process and content management system, which in the target functional IT ecosystem is positioned as a single window to the catalog of "internal services" of the enterprise, as well as as a tool for the operational work of managers and personnel when performing daily routine operations and assignments. In fact, this is an umbrella system, for it covers all the needs for obtaining and processing information essential for making decisions from the level of the general director to the personnel of the shop (branch), and is built-up on the principles of continuity of management and information processes.

Fig. 6 schematically shows a model of economic effects in the digital transformation of an enterprise, technologically based on the IT ecosystem, the integrating link of which is the corporate process and content management system.

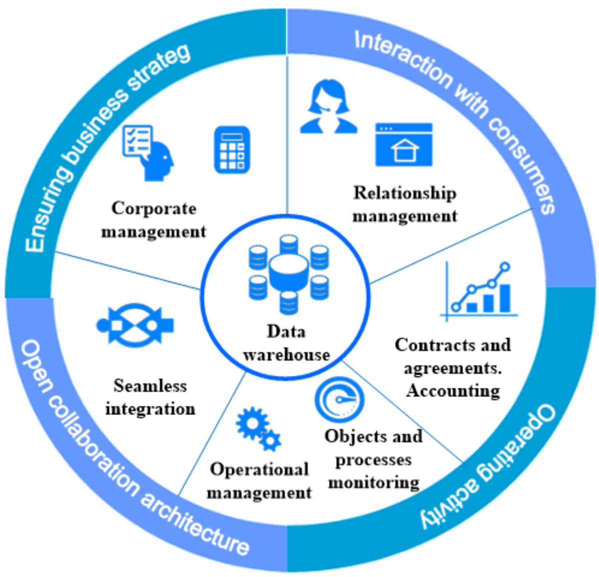

Fig. 5. Unified information space of a digital enterprise

Source: Authors

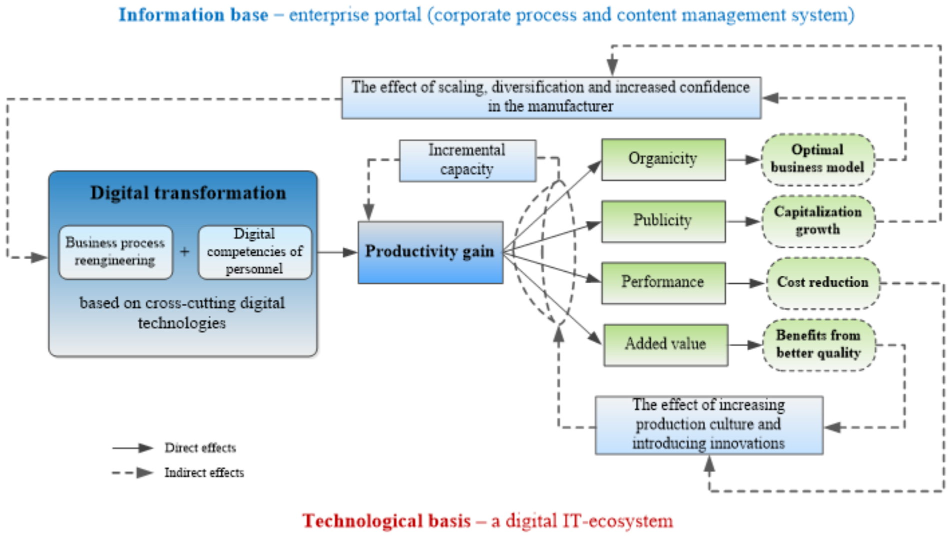

Fig. 6. Model of economic effects in digital transformation
Source: Authors

The key point that determines the success of the digital transformation is the ability of top management, following the developed strategy, to ensure an effective combination of employee competencies with innovative technologies in the process of transforming the production life cycle. In other words, the digital transformation strategy requires the designing of a separate, maximally detailed program for the creation and development of human resources (target motivation, advanced training of elder personnel, acceptance of the values of corporate culture, etc.). In this regard, it is necessary to separately note the change in the behavior patterns of the most active part of the population aged 20 to 35 years, where often, thanks to developed communications and the possibility of obtaining information, consumer values are re-estimated. For example, the opportunity to gain practical experience and build a positive resume for subsequent career growth may outweigh the value of the current material reward. Such trends in the formation of an active innovative style and susceptibility to constant changes should be monitored in the labor market, first of all, to attract talent. They should become one of the key factors in attracting capable young people to implement a long-term development strategy at the corporate and regional levels.

Conclusion

1. The applied model of the socio-economic system of a constituent entity of the Russian Federation is proposed for carrying out a systematic analysis of its macroeconomic indicators, which is necessary, firstly, to conduct a comprehensive assessment of the regions readiness for transformations towards the digitalization of the economy, and secondly, for reasonable goal-setting and determination priority areas of development for strategizing.

2. The example of St. Petersburg city shows that the decisive role in the process of the digital transformation of business should be taken by city-forming enterprises that have the appropriate infrastructure and the necessary resources, primarily qualified personnel.

3. The basis of the planned transformations of economic systems are IT ecosystems (digital platforms) that realize an integrated approach to management decisions using knowledge economy technologies such as predictive analytics, artificial intelligence, big data, cloud computing, etc. The best management decisions may only be taken, if the persons who undertake them and participate in the preparation have access to verified, relevant and structured information from reliable independent sources.

4. The main component of a digital transformation solution is a strategy, the completeness, quality, validity, and adequacy of which determines the effectiveness and success of not only the planned transformations, but the entire work as a whole. An enterprise digital transformation strategy should include full-scale marketing research, analysis of the external and internal environment, a list of planned and promising end-to-end technologies. Moreover, all this should be formalized in interconnected complex digitalization programs, synchronized in time and resources.

Directions for further research

The present article considers a reduced model of the socio-economic system of the region, which includes ten basic processes. When moving to the practical implementation of the proposed approach, for a more accurate assessment and development of recommendations on the choice of areas of advanced development (development of strategic priorities) for a specific region, the structure of the digital twin should be detailed. Therefore, further research will be associated with the selection and formalization of an additional set of “factor-indicator” couples. At the same time, for justifying the feasibility and effectiveness of the procedures for the digital transformation of economic systems, certain measures will be devoted to developing appropriate methods.

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STRATEGIC DEVELOPMENT OF THE MULTI-LEVEL SOCIO-ECONOMIC SYSTEM OF THE STATE IN THE DIGITAL ECONOMY

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The relevance of the study is due to the development of the digital economy in the Russian Federation. Forecasting, strategic planning in this aspect is a promising direction of socio-economic development of the state, as well as its constituent parts – regions, municipalities, enterprises (firms) – the latter being on the lower level of the economy forming its foundation. This area of research provides a methodological basis for the development and implementation of management decisions focused on priority areas of economic development of the state. The purpose of the study is to analyze and develop theoretical and methodological provisions of strategic and innovative development of the multi-level economic system of the state in the digital economy. Other objectives include the research and development of mathematical models of the lower level of the state economy of large corporations (clusters). To achieve these goals, the first part of the work examines the structure of a multi-level hierarchical system of the state economy aimed at solving the problems of strategic planning and management at individual levels of the state within the digital economy. In the second part, based on the analysis and theoretical studies of previously proposed mathematical models of enterprise development, we developed a mathematical model of a corporation (cluster). The cluster model takes into account both extensive and intensive factors of production development. The input data of the cluster model is, first, statistical information and, second, technological information of pre-production. It is shown that taken together statistical, technological information, as well as the relationship with consumers of products and with the financial (banking) sphere is characterized as “digital economy”. The direction of further research is related to the practical implementation of mathematical models and their use in the practice of forecasting the development of an industrial corporation (cluster).

Keywords: state, corporation, strategic development, statistical information, technological information, vector optimization

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СТРАТЕГИЧЕСКОЕ РАЗВИТИЕ МНОГОУРОВНЕВОЙ СОЦИАЛЬНО-ЭКОНОМИЧЕСКОЙ СИСТЕМЫ ГОСУДАРСТВА В УСЛОВИЯХ ЦИФРОВОЙ ЭКОНОМИКИ

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Актуальность исследования обусловлена развитием цифровой экономики в Российской Федерации. Прогнозирование, стратегическое планирование в этом аспекте является перспективным направлением социально-экономического развития государства, а также его составных частей: регионов, муниципальных образований и предприятий (фирм). Предприятия находятся на нижнем уровне экономики и которые являются ее основой. Это направление исследований создает методологическую основу разработки, реализации управленческих решений, ориентированных на приоритетные направления экономического развития государства. Цель исследования состоит в анализе и разработке теоретико-методологических положений стратегического и инновационного развития многоуровневой экономической системы государства в условиях цифровой экономики, а также в исследовании и формировании математических моделей нижнего уровня экономики государства крупных корпораций (кластеров). Для реализации этих целей в первой части работы исследованы структуры блоков иерархических многоуровневых систем экономики государства, направленная на решение задач стратегического планирования и управления на отдельных уровнях государства в условиях цифровой экономики. Во второй части на базе проведенного анализа и теоретических исследований раннее созданных математических моделей развития предприятия, мы разработали математическую модель корпорации (кластера). Математическая модель фирмы (кластера) учитывает экстенсивные и интенсивные производственные факторы развития. Входом математической модели кластера являются информация, представленная статистическими органами, а также технологическая информация подготовки производства. Показано, что в совокупности статистическая, технологическая информация, а также взаимосвязь с потребителями продукции и с финансовой (банковской) сферой характеризуется как «цифровая экономика». Дальнейшие исследования связаны с разработкой и внедрением математических моделей в практику прогнозирования развития промышленного кластера.

Ключевые слова: государство, корпорация, стратегическое развитие, статистическая информация, технологическая информация, векторная оптимизация

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Introduction

Forecasting, strategic planning is a promising direction of socio-economic development of the state and its constituent parts: firms (enterprises), municipalities, regions, which form the basis of the state's economy. This area of research is aimed at forming a methodological basis for the development and implementation of management decisions that are focused on priority areas of social and economic development of the state, which is reflected in related legal documents[1,2,3,4]. The theory of economic management, research objectives[5] as well as strategic development of industrial enterprises, corporations and the adoption of the optimal solutions are given much attention both in foreign countries [5, 7, 9, 12, 24, 28], and in the Russian Federation [1, 2, 3, 14–23, 29–34].

The social and economic processes of state development are quite complex and require a systematic [5, 7, 29], regional-balanced approach to management [6, 12]. Hence, state regulation to support such transformations is particularly important and relevant [30]. The forecast and dynamics of the development of regional and state economy are carried out by constructing mathematical models of both individual enterprises [20–22, 29], and municipalities [30], regions (subjects of the Russian Federation) [30], as well as the state as a whole. The forecast and development of the state economy requires legislative[6] support for decision-making, as well as mathematical [32, 33] software [30], information (including the digital economy [1, 2, 18, 19, 20]), and statistical [30]) support.

[1] The Constitution of the Russian Federation: Adopted by popular vote on December 12, 1993, with the amendments of 30.12.2008 No. 7-FKZ.
[2] Budget Code of the Russian Federation, Moscow: TK Velbi, Prospect Publishing House, 2010, 215 p.
[3] Tax Code of the Russian Federation. Part One [adopted by the State Duma on 16.07.1998, Approved by the Federation Council on 17.07.1998]. Access mode URL: http://www.consultant.ru/document/cons_doc_LAW_19671/
[4] Federal Law of the Russian Federation No. 172-FZ of June 28, 2014 "On Strategic Planning in the Russian Federation". http://www.rg.ru/2014/07/03/strategia-dok.html
[5] Putin's Message on January 15, 2020: all President Putin's proposals to the Federal Assembly http://kremlin.ru/events/president/news/62582
[6] Program "Digital Economy of the Russian Federation" Decree of the Government of the Russian Federation No. 1632-r of July 28, 2017, Moscow. http://static.government.ru/media/files/9gFM4FHj4PsB79I5v7yLVuPgu4bvR7M0.pdf

The object of the study is a multi-level management system of the state economy, including regions (subjects of the Russian Federation), municipal entities and enterprises (firms).

The subject of the research includes analytical, theoretical and methodological provisions for the strategic and innovative development of the multi-level economic system of the state in the digital economy.

The purpose of the study is to analyze and develop theoretical and methodological provisions for the strategic and innovative development of the multi-level economic system of the state in the digital economy. It also includes the research and formation of mathematical models of the lower level of the state economy of large corporations (clusters).

To achieve this goal, we have divided the work into two parts.

In the first part of the work, the hierarchical system (HS) of the multi-level economy of the state is investigated. In the study of the HS management of the state, four levels are considered: enterprises (firms), municipalities, subjects of the Russian Federation (regions), the state, and the world economy. The goals and objectives of strategic planning and management at the appropriate level are considered. We developed a modeling methodology to solve planning and management problems at individual levels of the state's HS within the digital economy.

In the second part, a study of the production activity of the company, the lower level of the state economy, is carried out. The functioning of the company is determined by a number of the following indicators: sales (revenue), profit, benefit, profitability. Modeling the development of the enterprise within the framework of modern (with one criterion) optimization methods allowed us to solve one directed development of the enterprise (firm), [21, 22, and 29]. Therefore, the development of economic theory is characterized by the study of the multiplicity of goals (criteria) of firm management [25, 30, and 31]. This class of problems includes multi-criteria (vector) problems of mathematical programming. The development of methods for solving vector problems is presented in [32, 33]. Vector problems and methods of their solution are used to create a high-quality management system, strategic development of industrial production, taking into account statistical, technological information and the digital economy.

The research methods are based on the theory of hierarchical systems research, as well as on the basis of economic and mathematical methods, the theory and methods of vector optimization. Methods of statistical analysis, systematization and generalization of the obtained results are used.

Results and discussion. The results are presented in three sections: "Management of a multi-level state system within the digital economy"; "Theoretical foundations of mathematical modeling of the development and management of an industrial enterprise: a cluster (the lower level of the hierarchical structure of the state)"; "Theory and methods of vector optimization as mathematical support for modeling in the digital economy of the state".

1. Managing the multi-level system of the state within the digital economy

The functioning of state authorities related to the management of the economic and social development of the state includes relations between the central governing bodies of the state, the subjects of the Russian Federation (regions), and municipalities, which are an integral part of the national policy of the state. In this aspect, we will adhere to V.I. Lenin's definition of politics as a "concentrated expression of the economy"[7]. This implies concentrated activity of the state's governing bodies in the conditions of the global environment of competing states.

The implementation of the state's economic policy is reflected in a certain system of indicators. These economic indicators are used as the goals of the socio-economic development of the state when solving problems in the implementation of these goals. The system of economic indicators and related goals is represented by the Types of Economic Activity (TEA). The objectives of the state's economic policy are reflected in the legislative, administrative, and economic laws and measures implemented by the central, constituent entities of the Russian Federation, and local authorities. The organizational structure of the

[7] Lenin V. I. Complete collection of works, 5 ed., vol. 42, p. 278.

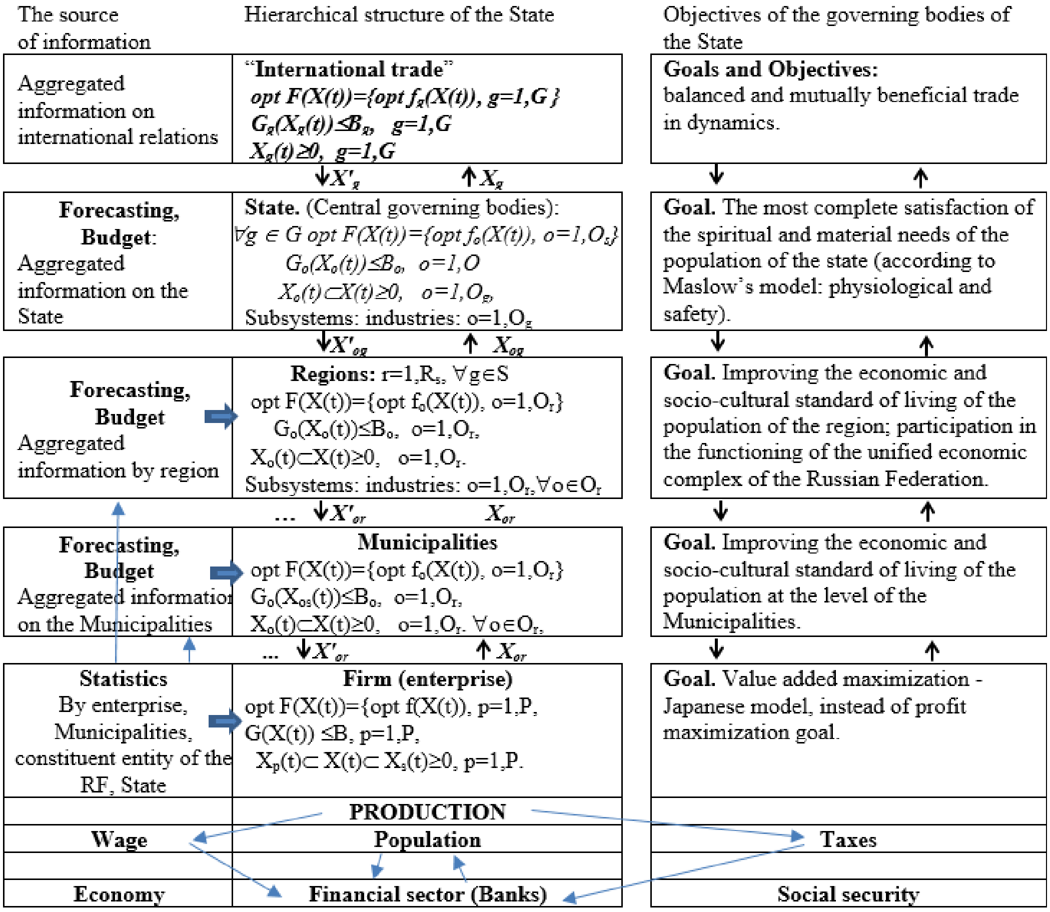

Fig. 1. Goals, tasks of management in a multilevel hierarchical system of the state in a digital economy

multi-level HS of the state economy is aimed at solving the problems of current, strategic planning and management at individual levels of the state in the digital economy (Fig. 1).

The goals of the current, strategic planning and management of the state's HS, presented in Fig. 1, include four levels: enterprises (firms), municipalities, regions (subjects of the Russian Federation), the state and the added level of the world economy.

The top level of the HS represents the highest management subsystem, which forms information for decision-making associated with international organizations, and coordinates the development of foreign trade operations of various countries. Coordination of foreign trade operations is carried out when solving the problems of balanced and mutually beneficial trade in dynamics. As a result of the decision, the amount of profit (income) is determined: $X_g, g=\overline{1,G}$, which the $g \in \boldsymbol{G}$ state will have when selling the corresponding goods to other countries.

- ***At the highest level of state HS*** management, we consider management subsystems, whose activities are related to the management of the economy of their countries. The target orientation of this level is determined by the most complete satisfaction of the material and spiritual needs of the population of the state, the growth of its standard of living (i.e., according to the Maslow model: the implementation of the first and second needs – physiological and safety). As a result, the public administration subsystem forms a vector of aggregated Types of Economic Activity (TEA) by industry: $o=\overline{1,O_g}$, including exports that could be mastered by this state: $X_{og}, o=\overline{1,O_g}, \ g \in G$. The received data is reported to the regional level.

• ***At the regional (second) level of government***, the mechanism of forecasting, planning and management is aimed, firstly, at improving the social and economic standard of living of the population of the region, and secondly, at participating in the all-Russian division of labor, as the functioning of a single economic complex of the Russian Federation with mutual benefits. The development of the region due to the intensification of the development of industry, the agricultural production should be carried out taking into account the rational use of natural resources and the development of resource-saving technologies. Regional current, strategic planning and management should be based on the production and economic activities of individual firms (enterprises) and their associations, which are the main suppliers of the region's products. The growth of the population's well-being is closely related to the growth of labor productivity and the increase in the volume of products produced in the region, quality improvement, competitiveness [6]. The above-stated global goals, assessments of the development of the region in the process of implementing production tasks, are divided into industry-level goals, which, in their essence, represent the solution of large sets of tasks.

• ***At the municipal (third) level of government***, the forecast, planning and management is aimed at improving the social and economic standard of living of the local government population.

In the Constitution of the Russian Federation, Article 12 states "Local self-government is recognized and guaranteed in the Russian Federation. Local self-government within the limits of its powers is independent. Local self-government bodies are not part of the system of state authorities".

It should be understood that it is in the municipalities, along with military facilities, that all industrial and agricultural enterprises are concentrated, which:

first, create the economic base for the development of the state's economy and the economic potential for the future development of the state;

secondly, it is these enterprises that determine the main tax revenues and form the revenue part of the budget of the Russian Federation, which determines the socio-economic development of the state, its protection.

With this in mind, we would like to see municipalities (MO) more actively participate in state activities. President V.V. Putin in his speech[8] said that currently only 1% of the total tax revenue remains in the Ministry of Defense. It is advisable to raise its level to 5%. Unfortunately, the progress on this issue has stalled. Each enterprise (firm), according to the legislation, pays taxes for the year, the size of which is approximately 20–25% of annual gross receipts. Thus, in an implicit form (de facto), the state owns 20–25% of fixed assets, and is obliged to supervise their safety, and better yet, their growth. If the local government were to transfer the state functions (de jure) related to the control of tax receipts (the Federal authorities will naturally collect taxes, as they do now), the level of tax receipts would increase, and as a result, the living (socio-economic) level of the population would increase. Moreover, if the level of tax collection exceeds some average level for the state, then part of the exceeded amount of taxes should remain at the disposal of the Ministry of Defense. And this is possible only when each enterprise of the Ministry of Defense increases the volume of production, as a rule, due to the growth of labor productivity.

At the level of (fourth) management of the firm (enterprise), the target orientation is determined by increasing the economic standard of living not only for shareholders, but also for all participants in production, who are represented by engineering, production, and management personnel. All participants in production equally form the profit of the firm (enterprise) and the maximum increase in labor productivity is only possible in their joint effort. The analysis of the company's production activity, theory, and software for the strategic development of the company (industrial cluster) using statistical information and the digital economy is the basis of this article [18–21, 29, 31].

Statistical information at the enterprise (firm) level is the source information, i.e. the base of the digital economy.

[8] Putin's Message on January 15, 2020: all President Putin's proposals to the Federal Assembly http://kremlin.ru/events/president/news/62582

Statistical information is generated from three sources: first, from consumers who are engaged in the material and technical support of production; second, from manufacturers who implement technological processes of production organization; and third, from manufacturers who sell manufactured goods and services. In accordance with the decision of the Board of the Eurasian Economic Commission of September 3, 2013. No. 185 “On Approval of the list of Statistical indicators of Official Statistical Information provided to the Eurasian Economic Commission by the Authorized Bodies of the Member States of the Customs Union and the Single Economic Space”, [34], all enterprises annually (quarterly) submit a number of macroeconomic indicators.

The main one is the Gross Domestic Product (in current prices), which includes information: quarterly, annual by type of economic activity (Appendix 1 in [34]), by institutional sectors (appendix 2 in [34]), by elements of end use (Appendix 3 in [34]), by elements of income (appendix 4 in [34]). These and other indicators, distributed across the entire state HS, are the digital economy. The information database is further used in the analysis of the development of the enterprise, the municipality, the region and the state as a whole.

2. Digital economy. Electronic (digital, web, Internet) economy is economic activity based on digital technologies (quote from Wikipedia) [1]. Within this definition, “it is not so much about the development and sale of software, but about electronic goods and services produced by e-business and e-commerce” [2, 18–21]. Hence, the digital economy cannot exist without the real and raw materials sectors, without production, which turns raw materials into products, without agriculture and without transport, delivering raw materials to the factory, products to the warehouse and goods from the warehouse to the store or to your home [1, 2]. Thus, the digital economy is not a complete economy, but its part, consisting of electronic goods and services. It is more correct to say not “digital economy”, but the digital sector of the economy. Let’s try to define the digital economy [30].

The “digital economy” is an information representation on paper and, above all, on electronic media: firstly, of all material resources (which include: land resources, manufacturing enterprises, firms, goods (including the process of creation and implementation), financial (including banks) and government organizations), and, secondly, of the population with its financial capabilities, which (material resources and population) together dynamically change in space and time.

To form the informational display of the “Digital Economy”, digital technologies or software have been developed, which represent technologies for collecting, storing (database), processing, searching, transmitting and presenting large-volume data. These information technologies for data collection and transmission are presented in general form (arrows) in the lower part of Fig. 1.

3. Theoretical foundations of mathematical modeling of the development and management of an industrial enterprise: cluster

3.1. Analysis of modern economic and mathematical models of the firm development

There are different mathematical models developed for an assessment of behavior of firms in society, formations of the purposes and tasks of the organization of management. The following models are currently used in the theory: maximizing profit, maximizing sales volume, maximizing growth, administrative behavior, the Japanese model directed on maximizing value added [29, 30].

The traditional firm theory recognizes that the behavior of a firm is defined by its only desire of maximizing profit (*model 1*).

The model of maximizing sales volume is the most widely known alternative of the model of maximizing profit. The model of maximizing sales is formed in two options: with criterion of maximizing sales under the condition of restricted resources (*model 2a*), and with criterion of minimizing prime cost while some volume of economic indicators is restricted (*model 2b*).

The model of maximizing growth (*model 3*) is characterized by a strategy with the cornerstone in continuous growth: long-term increase in production and sales [30].

The management theory of firm claims that the economic behavior of a firm is defined not by its owners, but the managers who have a purpose of maximizing sales volume and profit because of the income. The model of administrative behavior (*model 4*) includes the model of administrative benefit, the model of administrative prudence and the agency model [9].

The model of maximizing value added is a Japanese model (*model 5*) defined by that the value added is calculated as a difference between sales to the company for a certain time point and expenses (costs) of the goods of service acquired at external suppliers. Thereby the value added includes work, management, the capital, costs of profit. Such an approach implies that each worker and the shareholder of the firm maximizing value added knows that irrespective of economic conditions the priority has to be given to constant investments into capacities and the equipment, into researches and development, into development of the market. If there is a need to reduce remuneration to workers, the salary of the senior administrative personnel is reduced first. Japanese automakers and other companies, despite of economic conditions, seek to maximize value added in such a way year after year [30].

The emergence of such a variety of models indicates that none of them can adequately reflect the real life situations, which arise in practice of enterprise management. This results in new approaches (models) to the management of enterprises.

The economic theory of multiple goals stems from the fact that a firm has not one goal (sales, profit, growth), but a set of goals, which is a counterweight to single-criteria goals. Currently, a firm is a complex corporate system in which the organizational structure characterizes the hierarchy of subjects and objects of management. This management hierarchy corresponds to a hierarchy of interests and goals. First, the top management's interest is to increase the firm's prestige, improve its economic performance, and ensure its stability and sustainability. Secondly, it is in the interest of shareholders to raise higher dividends. Thirdly, managers' interest is aimed at improving their social status, making a good career, and ensuring income growth. Fourth, the interest of wage earners is to raise wages, get good working conditions, and improve their skills, professional growth, and so on. In the development of this direction, an approach based on a multi-purpose mathematical model is proposed. It is used in modeling the annual, strategic (long-term) development plan of the company.

3.2. Creation of mathematical model of the production plan of firm development

Currently, as it was stated above, there are some alternative mathematical behavior models of firms. We will unite the purposes of all models in the form of a vector of criteria. We will consider the restrictions of each model. We will present a vector of criteria and the restrictions in the form of a mathematical model, which represents a vector problem of mathematical programming.

Creation of mathematical model of the annual (strategic) plan of a firm assumes formation: a vector of variables, a vector of criteria (purposes) and restrictions imposed on the functioning of the firm [29, 30].

Vector of variables. Let us introduce a vector of variables:

$$X(t) = \left\{x_j, j = \overline{1, N}\right\},$$

where each component $j \in N$ determines the type $j = \overline{1, N}$ and the volume $x_j(t)$ of products, which included in production in the planned year of $t \in \boldsymbol{T}$. N is a set of indices of types (nomenclature) of products, works, and services. Restrictions of $u_j(t)$, $j \in N$ are imposed on the production variables $x_j(t)$, $j \in N$: they determine the probable volume of production of the j^{th} type. The values of $u_j(t)$, $j \in N$, as a rule, are obtained by the marketing department of the firm which conducts a research of the commodity market:

$$x_j(t) \le u_j(t), j = \overline{1, N}.$$

Vector of criteria which defines the functional objectives of the firm.

The firm production is characterized by a set of $\boldsymbol{K}$ technical-economic indicators. Let us represent the functional dependence of a $k \in \boldsymbol{K}$ economic indicator on the output of $X(t)$ using a $f_k(X(t))$ function, in the assumption that such functional dependence exists and is linear, i.e.:

$$\forall k \in \boldsymbol{K}, f_k\left(X(t)\right) = \sum\nolimits_{j=1}^{N} c_j^k x_j(t),$$

where c_j^k is a value of the k^{th} economic indicator (criterion) characterizing a unit of the j^{th} production type, $j \in \boldsymbol{N}$. In general, let us present a set of the indicators by a vector function:

$$F\left(X(t)\right) = \left\{ f_k\left(X(t)\right) = \sum\nolimits_{j=1}^{N} c_j^k x_j(t),\ k = \overline{1, K} \right\}. \tag{3.1}$$

Let us divide the whole set of the $\boldsymbol{K}$ criteria into three subsets $\boldsymbol{K_1}$, $\boldsymbol{K_2}$, $\boldsymbol{K_3}$.

The first $\boldsymbol{K_1}$ *subset*: $F_1(X(t)) \subset F(X(t))$ depends on organizational structure of the enterprises (the neoinstitutional theory). It is supposed that the firm consists of $\boldsymbol{Q}$ – a set of local enterprises (divisions), at each of them the development purposes functionally depend on the $f_q(X(t))$, $q \in \boldsymbol{Q}$ output of this q^{th} enterprise. Each q^{th} enterprise is presented by a set of criteria of $\boldsymbol{K}_q$, $q \in \boldsymbol{Q}$:

$$f_q\left(X(t)\right) = \left\{ f_{kq}\left(X(t)\right), k = \overline{1, K_q}, q \in \boldsymbol{Q} \right\}.$$

If $\boldsymbol{Q} = 1$, then is a standard definition of the firm. A set of criteria (purposes) of all enterprises is presented by a vector function:

$$F_1\left(X(t)\right) = \left\{ f_q\left(X(t)\right), q = \overline{1, K_1} \right\}, \boldsymbol{K_1} = \boldsymbol{Q}, \boldsymbol{K_1} \subset \boldsymbol{K}.$$

The second $\boldsymbol{K_2}$ *subset* defines the purposes of the firm in general: it is the highest managing subsystem. Each criterion $k = \overline{1, K_2}$ includes the corresponding indicators of all local subsystems and contains the nomenclature, volumes, technical and economic indicators of the products produced by the corporation as a whole:

$$F_2\left(X(t)\right) = \left\{ f_k\left(X(t)\right), k = \overline{1, K_2} \right\}, \boldsymbol{K_2} \subset \boldsymbol{K}.$$

The vector of $F_2(X(t))$ includes sales volumes of the made production, profits, value added, etc. It is desirable to maximize these indicators.

The third $\boldsymbol{K_3}$ *subset* includes economic indicators related to costs that are desirable to minimize:

$$F_3\left(X(t)\right) = \left\{ f_k\left(X(t)\right), k = \overline{1, K_3} \right\}, \boldsymbol{K_3} \subset \boldsymbol{K}.$$

Indicators (criteria) $F_3(X(t))$ characterize the minimization of material and labor costs, which together determine the cost of production. Economic indicators (criteria) $\boldsymbol{K_2}$, $\boldsymbol{K_3}$ represent the system characteristics of the corporation (firm). They determine the relationship between the firm and the society:

$$\boldsymbol{K_1} \cup \boldsymbol{K_2} \cup \boldsymbol{K_3} = \boldsymbol{K},$$

where $\boldsymbol{K}$ is the set of indicator (criteria) indices of the firm development in general.

The restrictions that are imposed when developing a plan include two groups. The first (main) group of restrictions is related to resource (technological) costs. They include restrictions on production capacity, labor, and material and technical resources. The second group of restrictions is determined by the planned indicators, which in the very least need to be obtained.

Resource restrictions. We assume that the dependence of resource costs on the volume of goods produced $X(t)=\{x_j,\ j=\overline{1,N}\}$ is linear:

$$\sum_{j=1}^{N} a_{ij}(t)x_j(t)\le b_i(t),\ i=\overline{1,M},\qquad (3.2)$$

where $a_{ij}(t),\ i=\overline{1,M},\ j=\overline{1,N}$ is a norm which characterizes the quantity of the i^{th} resource necessary for production of a unit of the j^{th} product type.

The set of indices of resources $\boldsymbol{M}$ includes:

a set of material resources $\boldsymbol{M}_{mat}\subset \boldsymbol{M}$, which characterizes the materials, semi-finished products, etc., used in production;

a set of labor resources $\boldsymbol{M}_{tr}\subset \boldsymbol{M}$ involved in production;

a set of funded resources (capacities) $\boldsymbol{M}_f\subset \boldsymbol{M}$ in the period $t\in \boldsymbol{T}$.

Similarly, (3.2) presents the costs of the i^{th} resource of the q^{th} division:

$$\sum_{j=1}^{N} a_{ij}^{q}(t)x_j(t)\le b_i^{q}(t),\ i=\overline{1,M_q},\ i=\overline{1,Q},$$

where $b_i^q(t),\ i=\overline{1,M_q},\ i=\overline{1,Q}$ is the value of the i^{th} resource which is available in the q^{th} division of the enterprise for the planned period. $\boldsymbol{M}_q$ is a set of resources types which are used in production in q^{th} division.

The restrictions connected with the planned indicators:

$$\sum_{j=1}^{N} c_i x_j(t)\ge b_k(t),\qquad (3.3)$$

where c_i is the value of the j^{th} economic indicator characterizing the production unit, b_k is the minimum value of the planned indicator which the firm should achieve in the planned period of time, $t\in \boldsymbol{T}$.

Variable expenses depend on the output:

$a_{ij}(t),\ i=\overline{1,M},\ j=\overline{1,N}$ is the i^{th} resource costs needed to produce a unit of the j^{th} type of production (norm), i, $\boldsymbol{M}$ are an index and a set of all types of resources (material, labor, etc.), i.e. the variable expenses changing in proportion to output and used by production of all types;

$G_i(X)=\sum_{j=1}^{N} a_{ij}(t)x_j(t)\le b_i(t),\ i=\overline{1,M}$ is the costs of the i^{th} resource of all production types.

We will present the production prime cost of a production unit as a sums of variable expenses:

$$a_j^p=\sum_{i=1}^{M_{mat}} p_i a_{ij}^{mat}+\sum_{i=1}^{M_{tr}} p_i a_{ij}^{tr}+\sum_{i=1}^{M_f} p_i a_{ij}^{f},\ j=\overline{1,N},\qquad (3.4)$$

where a_{ij}^{mat}, a_{ij}^{tr}, a_{ij}^{f} are costs of a unit of production and p_i is the cost of the material, labor, and accumulated resources respectively;

$A^p(t)=\{a_j^p(t),\ j=\overline{1,N}\}$ is a vector of the planned production prime cost of a unit of all types of production.

Constant expenses don't depend on the output. They are calculated per product unit a_j^{nak} (depreciation charges, administrative and managerial expenses, maintenance costs of buildings and the equipment). In general, the planned full prime cost of a unit of production is defined as the sum of production prime cost and of overhead costs:

$$a_j=a_j^p+a_j^{nak},\ j=\overline{1,N}.$$

The full prime a_j is a basis for formation of market value of production. We can define (as far as possible) the costs per production unit of similar goods of competitor company and compare them with a_j in a similar way.

The price of the p_j production unit of the j^{th} type follows from market researches or on the basis of a calculation of level of the price taking into account the pricing policy. Important role is played by methods of calculation of the settlement price from the prime cost of a_j, $j=\overline{1,N}$.

Profit: the gross profit per unit is calculated as a difference between the cost of p_j and variable expenses $\pi_j^{val} = p_j - a_j^p$, $j=\overline{1,N}$.

The profit on product sales in the firm as a whole equals:

$$\pi = \sum_{j=1}^{N} \pi_j x_j(t). \tag{3.5}$$

The value added is determined per a unit of production as a difference between the p_j cost and material inputs a_j^{mat} for production of j^{th} type:

$$p_j^{dob} = p_j - a_j^{mat},\ j=\overline{1,N}, \tag{3.6}$$

where $a_j^{mat} = \sum_{i=1}^{M_{mat}} p_i a_{ij}$, $j=\overline{1,N}$ is the cost of material inputs per unit of the j^{th} production type arriving from external producers.

Using the calculated indicators (3.1)–(3.6), we construct the above described theoretical models.

Model 1: maximizing profit. Define:

$$max\ f(X(t)) \equiv \sum_{j=1}^{N} \pi_j x_j(t) \tag{3.7}$$

at restrictions

$$\sum_{j=1}^{N} a_{ij}(t) x_j(t) \le b_i(t),\ i=\overline{1,M}, \tag{3.8}$$

$$x_j(t) \le u_j(t),\ j=\overline{1,N}. \tag{3.9}$$

Model 2a: maximizing sales volume. Define:

$$max\ f(X(t)) \equiv \sum_{j=1}^{N} p_j x_j(t), \tag{3.10}$$

at restrictions

$$\sum_{j=1}^{N} a_{ij}(t) x_j(t) \le b_i(t),\ i=\overline{1,M}, \tag{3.11}$$

$$x_j(t) \le u_j(t),\ j=\overline{1,N}. \tag{3.12}$$

Model 2b: minimization of total expenses. Define:

$$min\ f(X(t)) \equiv \sum_{i=1}^{M} c_i \sum_{j=1}^{N} a_{ij}(t) x_j(t), \tag{3.13}$$

at restrictions

$$\sum_{j=1}^{N} c_j^k x_j(t) \ge b_k(t),\ k \in K, \tag{3.14}$$

$$x_j(t) \le u_j(t),\ j = \overline{1,N}, \tag{3.15}$$

where c_j^k is the economic indicator characterizing a unit of the j^{th} type of production, b_k is a set economic indicator characterizing such volume of production at which $b_k(t)$ has to be reached (≥).

Model 3: maximizing growth. Define:

$$max\ f(X(t)) \equiv \sum_{j=1}^{N} \pi_j x_j(t), \tag{3.16}$$

at restrictions

$$\sum_{j=1}^{N} a_{ij}(t) x_j(t) \le b_i(t) + \Delta b_i(t + \Delta t),\ i = \overline{1,M}, \tag{3.17}$$

$$x_j(t) \le u_j(t),\ j = \overline{1,N}, \tag{3.18}$$

where $\Delta b_i(t + \Delta t)$ is a planned gain of volume of resources as of the planned period Δt which is created due to depreciation charges, profit, or of loans.

Model 4: administrative behavior. Define:

$$max\ f(X(t)) \equiv \sum_{j=1}^{N} p_j^z x_j(t), \tag{3.19}$$

at restrictions

$$\sum_{j=1}^{N} a_{ij}(t) x_j(t) \le b_i(t),\ i = \overline{1,M}, \tag{3.20}$$

$$x_j(t) \le u_j(t),\ j = \overline{1,N}, \tag{3.21}$$

where p_j^z is the economic indicator determines the salary volume from production and sale of a unit of the j^{th} type of production.

Model 5: maximizing value added, Japanese model. Define:

$$max\ f(X(t)) \equiv \sum_{j=1}^{N} p_j^{dob} x_j(t), \tag{3.22}$$

at restrictions

$$\sum_{j=1}^{N} a_{ij}(t) x_j(t) \le b_i(t),\ i = \overline{1,M}, \tag{3.23}$$

$$x_j(t) \le u_j(t),\ j = \overline{1,N}, \tag{3.24}$$

where p_j^{dob} is the economic indicator (3.6) which determines the value added volume for the production and sale of a unit of the j^{th} type of production.

Economic and mathematical models: the model 1 (3.7)–(3.9), ..., model 5 (3.22)–(3.24) represent the current state of mathematical modeling of production systems.

3.3. Construction of a mathematical model of a manufacturing company in the form of a vector linear programming problem

The economic theory of plurality of the purposes assumes that the listed above purposes of all models actually exist and have to be considered simultaneously. We will present such objectives in a model of the annual plan of the enterprise in the form of a vector problem of linear programming:

$$opt\ F\left(X\left(t\right)\right)=\left\{max\ F_1\left(X\left(t\right)\right)=\left\{max\ f_q\left(X\left(t\right)\right)= \right.\right.$$
$$\left.\left. =\left\{max\ f_{kq}\left(X\left(t\right)\right)\equiv\sum\nolimits_{j=1}^{N_q}c_j^k x_j\left(t\right),\ k=\overline{1,K_q}\right\},\ q=\overline{1,Q}\right\}, \tag{3.25}$$

$$max\ F_2\left(X\left(t\right)\right)=\left\{max\ f_k\left(X\left(t\right)\right)\equiv\sum\nolimits_{j=1}^{N}c_j^k x_j\left(t\right),\ k=\overline{1,K_2}\right\}, \tag{3.26}$$

$$min\ F_3\left(X\left(t\right)\right)=\left\{min\ f_k\left(X\left(t\right)\right)\equiv\sum\nolimits_{i=1}^{M}c_i\sum\nolimits_{j=1}^{N}a_{ij}\left(t\right)x_j\left(t\right),\ k=\overline{1,K_3}\right\}, \tag{3.27}$$

at restrictions

$$\sum\nolimits_{j=1}^{N}a_{ij}\left(t\right)x_j\left(t\right)\le b_i\left(t\right),\ i=\overline{1,M}, \tag{3.28}$$

$$\sum\nolimits_{j=1}^{N_q}a_{ij}^q x_j\left(t\right)\le b_i^q\left(t\right),\ i=\overline{1,M_q},\ q=\overline{1,Q}, \tag{3.29}$$

$$\sum\nolimits_{j=1}^{N}c_j^k x_j\left(t\right)\ge b_k\left(t\right),\ k\in K, \tag{3.30}$$

$$0\le x_j\left(t\right)\le u_j\left(t\right),\ j=\overline{1,N}, \tag{3.31}$$

where $F(X(t))$ is vector criterion (2.25), the set of criteria of which is subdivided into three subsets:

$\boldsymbol{K_1}$ is a subset of criteria of the divisions of the firm, $k=\overline{1,K_q}$, $q=\overline{1,Q}$, $\boldsymbol{K_1}$ = Q;

$\boldsymbol{K_2}$ is a subset of criteria each component of which should be maximized (sales volumes of the made production, profits, value added, etc.);

$\boldsymbol{K_3}$ is a subset of criteria aimed at minimizing the indicators connected with prime cost of products; $\boldsymbol{K_2}$, $\boldsymbol{K_3}$ are the system criteria characterizing the firm in general (3.26), (3.27):

$$\boldsymbol{K_1}\cup\boldsymbol{K_2}\cup\boldsymbol{K_3}=\boldsymbol{K}.$$

In (3.25), the vector of criteria of $F(X(t))$ reflects the purposes of all models in total: (3.7)–(3.9) is the model of profit, ..., (3.22)–(3.24) is the model of maximizing value added;

$X=\left\{x_j\left(t\right),\ j=\overline{1,N}\right\}$ is a vector of variables each component of which defines the quantity of the j^{th} type products included in the plan;

$c_j^k,\ j=\overline{1,N}$ is a set of economic indicators of the k^{th} $k=\overline{1,K}$ type characterizing a unit of the j^{th} type of production.

A set of restrictions (3.28)–(3.31) which in total reflect the restrictions of all models under consideration: profits (3.8) – (3.9), ..., models of maximizing value added (3.23) – (3.24).

We will notice that a problem of definition:

$$\forall q\in\boldsymbol{Q},max\ f_q\left(X\left(t\right)\right)=\left\{max\ f_{kq}\left(X\left(t\right)\right)\equiv\sum\nolimits_{j=1}^{N_q}c_j^k x_j\left(t\right),\ k=\overline{1,K_q}\right\},$$

at restrictions (3.27)–(3.31) represents a model of a separate division of the firm in a form of a vector problem of linear programming.

For the solution of a vector problem of linear programming (3.25)–(3.31), the methods based on normalization of criteria and the principle of the guaranteed result are used [31, 32].

4. A vector problem of mathematical programming

A vector problem in mathematical programming (VPMP) is a standard mathematical-programming problem including a set of criteria, which, as a whole, represent a vector of criteria.

It is important to distinguish between uniform and non-uniform VPMP:

A uniform maximizing VPMP is a vector problem in which each criterion is directed towards maximizing;

A uniform minimizing VPMP is a vector problem in which each criterion is directed towards minimizing;

A non-uniform VPMP is a vector problem in which the set of criteria is shared between two subsets (vectors) of criteria (maximization and minimization respectively), e.g., inhomogeneous VPMP is a combination of two types of homogeneous problems.

According to these definitions, we will present a VPMP with non-uniform criteria in the following form:

$$Opt\ F(X) = \{\max F_1(X) = \{\max f_k(X), k = \overline{1, K_1}, \tag{4.1}$$

$$\min F_2(X) = \{\min f_k(X), k = \overline{1, K_2}\}, \tag{4.2}$$

$$G(X) \le B, \tag{4.3}$$

$$X \ge 0, \tag{4.4}$$

where $X = \{x_j, j = \overline{1, N}\}$ is a vector of material variables of an N-dimensional Euclidean space of R^N, (notation $j = j = \overline{1, N}$ is equivalent to $j = 1,..., N$);

$F(X)$ is a vector function (vector criterion) having K which is a function component (K is the power of the $\boldsymbol{K}$ set): $F(X) = \{f_k(X), k = \overline{1, K}\}$. The $\boldsymbol{K}$ set consists of the $\boldsymbol{K}_1$, subset of maximization criteria and the $\boldsymbol{K}_2$ subset of minimization; $\boldsymbol{K} = \boldsymbol{K}_1 \cup \boldsymbol{K}_2$, therefore we introduce an "*opt*" notation of the operation, which includes *max* and *min*;

$F_1(X) = \{f_k(X), k = \overline{1, K_1}\}$ is a maximizing vector criterion, K_1 is the number of criteria, and $K_1 \equiv \overline{1, K_1}$ is a set of maximizing criteria (problem (4.1), (4.3), (4.4) represents VPMP with the homogeneous maximizing criteria). Let's further assume that $f_k(X), k = \overline{1, K_1}$ are continuous concave functions (we will sometimes call them the maximizing criteria);

$F_2(X) = \{f_k(X), k = \overline{1, K_2}\}$ is a vector criterion in which each component is minimized, $K_2 \equiv \equiv \overline{K_1 + 1, K} \equiv \overline{1, K_2}$ are a set of minimization criteria, $\boldsymbol{K}_2$ is the number of criteria (the problems (4.2)–(4.4) are VPMP with the homogeneous minimization criteria). We assume that $f_k(X), k = \overline{1, K_2}$ are continuous convex functions (we will sometimes call them the minimization criteria), i.e., $\boldsymbol{K}_1 \cup \boldsymbol{K}_2 = \boldsymbol{K}$, $\boldsymbol{K}_1 \subset \boldsymbol{K}, \boldsymbol{K}_2 \subset \boldsymbol{K}$.

$G(X) \le B, X \ge 0$ is standard restrictions, $g_i(X) \le b_i, i = 1,..., M$ where b_i is a set of real numbers, and the $g_i(X)$ functions are assumed to be continuous and convex.

$$\boldsymbol{S} = \{X \in \boldsymbol{R}^n \mid X \ge 0, G(X) \le B, X^{min} \le X \le X^{max}\} \ne \varnothing,$$

where the set of admissible points set by standard restrictions (4.3)–(4.4) is not empty and represents a compact.

The vector minimization function (criterion) $F_2(X)$ can be transformed to the vector maximization function (criterion) by the multiplication of each component of $F_2(X)$ by minus one. The vector criterion of $F_2(X)$ is introduced into the VPMP (4.1)–(4.4) to show that, in the problem, there are two subsets of criteria of $\boldsymbol{K}_1$, $\boldsymbol{K}_2$ with essentially different directions of optimization.

We assume that the optimum points received by each criterion do not coincide for at least two criteria. If all points of an optimum coincide among themselves for all criteria, then we regard the decision as trivial.

5. Theory and methods of vector optimization as mathematical support for modeling in the digital economy of the state

The theory of vector optimization includes theoretical foundations (axioms) and methods of solving vector problems both with equivalent criteria and with the given criterion priority. The theory is a basis of mathematical apparatus of modeling of the "object for optimal decision-making".

As an "object of decision-making", we consider the socio-economic development of the state, including objects at the level of: firms (enterprises), municipalities, regions and the state as a whole. We presented the axioms and methodology for solving vector optimization problems (4.1)–(4.4) with equivalent criteria and a given criterion priority. [32, 33].

5.1. The axioms and the principle of optimality for vector optimization with the equivalent criteria

Definition 1. (*Definition of the relative estimate of the criterion*).

Let us introduce a notation:

$$\lambda_k(X)=\frac{f_k(X)-f_k^0}{f_k^*-f_k^0},\ \forall k\in\boldsymbol{K} \tag{5.1}$$

in vector problem (4.1)–(4.4), which is a relative estimate of the $k\in\boldsymbol{K}$ criterion at the point of $X\in\boldsymbol{S}$;

f_k^* is the value of the k^{th} criterion at the point of optimum X_k^*, obtained in vector problem (4.1)–(4.4) for the individual k^{th} criterion; f_k^0 is the worst value of the k^{th} criterion (anti optimum) at the X_k^0 point (superscript 0 for zero) on the admissible set $\boldsymbol{S}$ in vector problem (4.1)–(4.4);

The value of f_k^0 is the lowest value of the k^{th} criterion in the *max* problem (4.1), (4.3), (4.4): $f_k^0=min_{X\in S}f_k(X)\forall k\in K_1$, and in the *min* problem, f_k^0 is the greatest: $f_k^0=max_{X\in S}f_k(X)\forall k\in$ $\in K_2$.

First, the relative estimate of the $\lambda_k(X)$ $\forall$ $k\in K$, is performed in relative units; secondly, the relative estimate of the $\lambda_k(X)$ $\forall$ $k\in K$ in the admissible set changes from zero in the X_k^0 point $\left(\forall k\in\boldsymbol{K}\ \lim_{X_{\rightarrow}\rightarrow X_k^0}\lambda_k(X)=0\right)$ to one at the optimum X_k^* point of an optimum of $X_k^*\left(\forall k\in\boldsymbol{K}\ \lim_{X_{\rightarrow}\rightarrow X_k^*}\times\right.$ $\left.\times\lambda_k(X)=1\right)$, therefore

$$\forall k\in\boldsymbol{K}\ 0\le\lambda_k(X)\le1, X\in\boldsymbol{S}. \tag{5.2}$$

This allows a comparison of the criteria, measured in relative units, and their use in joint optimization.

Axiom 1. (About equality and equivalence of criteria in an admissible point of vector problems).

In the VPMP, two criteria with the indices $k\in K$, $q\in K$ shall be considered as equal in the $X\in S$ point, if relative estimates of the k^{th} and q^{th} criterion are equal in this point, i.e. $\lambda_k(X)=\lambda_q(X), k,q\in K$. We will consider criteria equivalent in the VPMP, if in the $X\in S$ point when numerically comparing the relative estimates of $\lambda_k(X), k=\overline{1,K}$, there are no conditions about priorities of criteria imposed on each criterion of $f_k(X), k=\overline{1,K}$, and, respectively, relative estimates of $\lambda_k(X)$.

Definition 2. (*Definition of a minimum level among all relative estimates of criteria*).

The relative level λ in the vector problem represents the lower estimate of a point of $X\in S$ among all relative estimates of $\lambda_k(X), k=\overline{1,K}$:

$$\forall X\in\boldsymbol{S}\ \lambda\le\lambda_k(X), k=\overline{1,K}, \tag{5.3}$$

the lower level for performance of a condition (5.3) in the admissible point of $X\in S$ is determined by a formula

$$\forall X\in\boldsymbol{S}\ \lambda=min_{k\in K}\lambda_k(X). \tag{5.4}$$

Ratios (5.3) and (5.4) are interconnected. They serve as transition from operation (5.4) of definition of *min* to restrictions (5.3) and vice versa.

The lower relative λ level allows uniting all criteria in the vector problem by one numerical characteristic of λ and to perform certain operations with it, thereby, at the same applying these operations to all the criteria measured in relative units. The λ level functionally depends on the $X \in \boldsymbol{S}$ variable, therefore by changing X, we can change the lower λ level.

Further, we formulate the rule of searching of the optimum solution.

Definition 3. (*The principle of an optimality with equivalent criteria*).

The VPMP with equivalent criteria is solved, if we find such a point of $X^o \in \boldsymbol{S}$ and such a maximum level of λ^o (superscript o for optimum) among all relative estimates that

$$\lambda^o = \boldsymbol{max}_{X\in \boldsymbol{S}}\boldsymbol{min}_{\boldsymbol{k}\in \boldsymbol{K}}\lambda_k\left(X\right). \tag{5.5}$$

Using interrelation of Eqs. (5.3) and (5.4), we transform a maximin problem (5.5) into an extreme problem

$$\lambda^o = \boldsymbol{max}_{X\in \boldsymbol{S}}\lambda, \tag{5.6}$$

at restrictions

$$\lambda \le \lambda_k\left(X\right), k = \overline{1,K}. \tag{5.7}$$

Let's call optimization problem (5.6)–(5.7) the λ-problem.

λ-problem (5.6)–(5.7) has (N+1) dimension, and consequently the result of solving λ-problem (5.6)–(5.7) consists in an optimum vector of $\boldsymbol{X}^{\boldsymbol{o}} \in R^{N+1}$, in which the $(N+1)^{\text{th}}$ component is essentially the λ^o value. Thus in the optimum point of $\boldsymbol{X}^{\boldsymbol{o}} = \left\{x_1^o, x_2^o, ..., x_N^o, x_{N+1}^o\right\}$, the component $x_{N+1}^o = \lambda^o$, and the $(N+1)$ component of the $\boldsymbol{X}^o$ vector is selected in view of its specificity.

The received pair of $\{\lambda^o, X^o\} = \boldsymbol{X}^o$ characterizes the optimum solution of λ-problem (5.6)–(5.7) and at the same time is the solution to VPMP (4.1)–(4.4) with the equivalent criteria, solved on the basis of normalization of criteria and the principle of the guaranteed result. In the optimum solution of $\boldsymbol{X}^o = \{\lambda^o, X^o\}$, we will denote X^o as an optimal point, and λ^o as a maximum level.

The following theorem is an important result of the algorithm for solving vector problems (4.1)–(4.4) with equivalent criteria [32].

Theorem 1. (*The theorem of the two inconsistent criteria in the vector problem of mathematical programming with equivalent criteria*).

In the convex VPMP with the equivalent criteria which is solved on the basis of normalization of criteria and the principle of the guaranteed result, in an optimum point of $\boldsymbol{X}^o = \{\lambda^o, X^o\}$, there are always two criteria: let us denote them with indices $q \in \boldsymbol{K}, p \in \boldsymbol{K}$ (which in a sense are the most inconsistent in the $k = \overline{1,K}$ criteria set), for which the following equality holds:

$$\lambda^o = \lambda_q\left(X^o\right) = \lambda_p\left(X^o\right), q, p \in \boldsymbol{K}, X \in \boldsymbol{S}, \tag{5.8}$$

and other criteria are determined by inequalities:

$$\lambda^o \le \lambda_k\left(X^o\right), \forall k \in \boldsymbol{K}, q \ne p \ne k. \tag{5.9}$$

5.2. Axioms and the principle of optimality of vector optimization with a criterion priority

To develop the methods of solving the vector optimization problems with a priority of criterion, we use the following definitions:

Priority of one criterion of vector problems, with a criterion priority over other criteria;

Numerical expression of a priority;

Set priority of a criterion;

Lower (minimum) level among all criteria with a priority of one of them;

Subset of points with priority by criterion (Axiom 2);

The principle of optimality of the solution of problems of vector optimization with the set priority of one of the criteria, and related theorems.

For more details, see [32, 33].

Definition 4. (*About the priority of one criterion over the other*).

The criterion of $q \in \boldsymbol{K}$ in the vector problem of Eqs. (4.1)–(4.4) in a point of $X \in \boldsymbol{S}$ has priority over other criteria of $k = \overline{1,K}$, and the relative estimate of $\lambda_q(X)$ by this criterion is greater than or equal to relative estimates of $\lambda_k(X)$ of other criteria, i.e.:

$$\lambda_q(X) \geq \lambda_k(X), k = \overline{1,K}, \tag{5.10}$$

and a strict priority for at least one criterion of $t \in \boldsymbol{K}$, $\lambda_q(X) > \lambda_k(X)$, $t \neq q$, and for other criteria of $\lambda_q(X) \geq \lambda_k(X), k = \overline{1,K}, k \neq t \neq q$.

Introduction of the definition of a priority of criterion $q \in \boldsymbol{K}$ in the vector problem of Eqs. (4.1)–(4.4) executed the redefinition of the early concept of a priority. Earlier the intuitive concept of the importance of this criterion was outlined, now this "importance" is defined as a mathematical concept: the higher the relative estimate of the q^{th} criterion compared to others, the more important it is (i.e., has higher priority), and the highest priority at a point of an optimum is $X_k^*, \forall q \in \boldsymbol{K}$.

From the definition of a priority of criterion of $q \in \boldsymbol{K}$ in the vector problem of Eqs. (4.1)–(4.4), it follows that it is possible to reveal a set of points $\boldsymbol{S}_q \subset \boldsymbol{S}$ that is characterized by $\lambda_q(X) \geq \lambda_k(X), \forall k \neq q$, $\forall X \in \boldsymbol{S}_q$. However, the answer to whether a criterion of $q \in \boldsymbol{K}$ at a point of the set $\boldsymbol{S}_q$ has more priority than others do remains open. For clarification of this question, we define a communication coefficient between a couple of relative estimates of q and k that, in total, represent a vector:

$$P^q(X) = \left\{ p_k^q(X) \middle| k = \overline{1,K} \right\}, q \in \boldsymbol{K}\ \forall X \in \boldsymbol{S}_q.$$

Definition 5. (*About numerical expression of a priority of one criterion over another*).

In the vector problem of Eqs. (4.1) and (4.4), with priority of the q^{th} criterion over other criteria of $k = \overline{1,K}$, for $\forall X \in \boldsymbol{S}_q$, and a vector of $P^q(X)$ which shows by how many times a relative estimate of $\lambda_q(X)$, $q \in \boldsymbol{K}$, is greater than other relative estimates of $\lambda_k(X), k = \overline{1,K}$, we define a numerical expression of the priority of the q^{th} criterion over other criteria of $k = \overline{1,K}$ as:

$$P^q(X) = \left\{ p_k^q(X) = \frac{\lambda_q(X)}{\lambda_k(X)}, k = \overline{1,K} \right\},$$

$$p_k^q(X) \geq 1, \forall X \in \boldsymbol{S}_q \subset S, k = \overline{1,K}, \forall q \in \boldsymbol{K}. \tag{5.11}$$

This definition of priority in the form of the ratio $p_k^q(X) = \dfrac{\lambda_q(X)}{\lambda_k(X)}, k = \overline{1,K}, \forall q \in \boldsymbol{K}$ is called a *numerical expression of the priority* of the q^{th} criterion over the other criteria $k = \overline{1,K}$.

Definition 6. (*About the set numerical expression of a priority of one criterion over another*).

In the vector problem of Eqs. (4.1)–(4.4) with a priority of criterion of $q \in \boldsymbol{K}$ for $\forall X \in \boldsymbol{S}$, vector $P^q = \left\{ p_k^q, k = \overline{1,K} \right\}$ is considered to be set by the person making decisions (i.e., the decision-maker) if every component of this vector is set. Set by the decision-maker, the p_k^q component, from the point of view of the decision-maker, shows by how many times a relative estimate of $\lambda_q(X)$, $q \in \boldsymbol{K}$ is greater than other relative estimates of $\lambda_k\left(X\right), k = \overline{1,K}$. The vector of $p_k^q, k = \overline{1,K}$, is the numerical expression of the priority of the q^{th} criterion over other criteria of $k = \overline{1,K}$:

$$P^q\left(X\right) = \left\{ p_k^q\left(X\right), k = \overline{1,K} \right\}, \; p_k^q\left(X\right) \geq 1, \forall X \in \boldsymbol{S}_q \subset S,$$
$$k = \overline{1,K}, \forall q \in \boldsymbol{K}. \tag{5.12}$$

The vector problem of Eqs. (4.1)–(4.4), in which the priority of any criteria is set, is called a vector problem with the set priority of criterion. The problem of a priorities vector arises when it is necessary to determine the point $X^{\text{o}} \in \boldsymbol{S}$ by the set vector of priorities. In the comparison of relative estimates with a priority of criterion of $q \in \boldsymbol{K}$, as well as in a problem with equivalent criteria, we define the additional numerical characteristic of λ which we will refer to as *the level*.

Definition 7. (*About the lower level among all relative estimates with a criterion priority*).

The λ level is the lowest among all relative estimates with a priority of criterion $q \in \boldsymbol{K}$ such that:

$$\lambda \leq p_k^q \lambda_k\left(X\right), k = \overline{1,K}, q \in \boldsymbol{K}, \forall X \in \boldsymbol{S}_q \subset S. \tag{5.13}$$

The lower level for the performance of the condition in Eq. (5.13) is defined as:

$$\lambda = min_{k \in K} p_k^q \lambda_k\left(X\right), q \in \boldsymbol{K}, \forall X \in \boldsymbol{S}_q \subset S. \tag{5.14}$$

Eqs. (5.13) and (5.14) are interconnected and serve as a further transition from the operation of determining the *min* to restrictions, and vice versa. In Section 3.1, we gave the definition of a Pareto optimal point $X^{\text{o}} \in \boldsymbol{S}$ with equivalent criteria. Considering this definition as an initial one, we will construct a number of axioms dividing an admissible set of $\boldsymbol{S}$ into, first, a subset of Pareto optimal points S^{o}, and, secondly, a subset of points $\boldsymbol{S}_q \subset \boldsymbol{S}$, $q \in \boldsymbol{K}$, with priority for the q^{th} criterion.

Axiom 2. (About a subset of points, priority by criterion in the VPMP).

In the vector problem of Eqs. (4.1)–(4.4), the subset of points $S_q \subset S$ is called the area of priority of criterion of $q \in K$ over other criteria, if

$$\forall X \in S_q \; \forall k \in K \; \lambda_q\left(X\right) \geq \lambda_k\left(X\right), q \neq k.$$

This definition extends to a set of Pareto optimal points S^{o} that is given by the following definition.

Axiom 2a. (About a subset of points, priority by criterion, on Pareto's great number in a vector problem).

In the VPMP, a subset of points $\boldsymbol{S}_q^o \subset \boldsymbol{S}^o \subset S$ is called the area of a priority of the $q \in \boldsymbol{K}$ criterion over other criteria, if $\forall X \in S_q^o \; \forall k \in K \; \lambda_q\left(X\right) \geq \lambda_k\left(X\right), q \neq k.$

In the following we provide explanations.

Axiom 2 and 2a allow breaking the vector problem in Eqs. (4.1)–(4.4) into an admissible set of points $\boldsymbol{S}$, including a subset of Pareto optimal points, $\boldsymbol{S}^{\text{o}} \subset \boldsymbol{S}$, and subsets:

one subset of points $\boldsymbol{S}' \subset \boldsymbol{S}$ where criteria are equivalent, and a subset of points of $\boldsymbol{S}'$ crossing with a subset of points $\boldsymbol{S}^{\text{o}}$, allocated to a subset of Pareto optimal points at equivalent criteria $\boldsymbol{S}^{\text{oo}} = \boldsymbol{S}' \cap \boldsymbol{S}^{\text{o}}$. As will be shown further, this consists of one point of $X^{\text{o}} \in \boldsymbol{S}$, i.e.

$$X^o = \boldsymbol{S}^{oo} = \boldsymbol{S}' \cap \boldsymbol{S}^o, \boldsymbol{S}' \in \boldsymbol{S}, \boldsymbol{S}^o \subset \boldsymbol{S}.$$

"$\boldsymbol{K}$" subsets of points where each criterion of $q=\overline{1,K}$ has a priority over other criteria of $k=\overline{1,K}$, $q \neq k$, and thus breaks, first, sets of all admissible points $\boldsymbol{S}$, into subsets $\boldsymbol{S}_q \subset \boldsymbol{S}$, $q=\overline{1,K}$ and, second, a set of Pareto optimal points, $\boldsymbol{S}^o$, into subsets $\boldsymbol{S}_q^o \subset \boldsymbol{S}_q \subset \boldsymbol{S}$, $q=\overline{1,K}$. This yields:

$$\boldsymbol{S}'U\left(U_{q\in K}\boldsymbol{S}_q^o\right) \equiv \boldsymbol{S}^o, \boldsymbol{S}_q^o \subset \boldsymbol{S}^o \subset \boldsymbol{S}, q=\overline{1,K}.$$

We note that the subset of points $\boldsymbol{S}_q^o$, on the one hand, is included in the area (a subset of points) of priority of criterion of $q \in \boldsymbol{K}$ over other criteria: $\boldsymbol{S}_q^o \subset \boldsymbol{S}^o \subset \boldsymbol{S}$, and, on the other, in a subset of Pareto optimal points $\boldsymbol{S}_q^o \subset \boldsymbol{S}^o \subset \boldsymbol{S}$.

Axiom 2 and the numerical expression of priority of criterion (Definition 5) allow the identification of each admissible point of $X \in \boldsymbol{S}$ (by means of vector):

$P^q(X)=\left\{p_k^q(X)=\dfrac{\lambda_q(X)}{\lambda_k(X)}, k=\overline{1,K}\right\}$, to form and choose:

a subset of points by priority criterion $\boldsymbol{S}_q$, which is included in a set of points $\boldsymbol{S}$, $\forall q \in \boldsymbol{K}\, X \in \boldsymbol{S}_q \subset \boldsymbol{S}$, (such a subset of points can be used in problems of clustering, but is beyond this article);

a subset of points by priority criterion $\boldsymbol{S}_q^o$, which is included in a set of Pareto optimal points $\boldsymbol{S}^o$, $\forall q \in K$, $X \in \boldsymbol{S}_q^o \subset \boldsymbol{S}^o$.

Thus, full identification of all points in the vector problem of Eqs. (4.1)–(4.4) is executed in sequence as:

Set of admissible points $X \in \boldsymbol{S} \rightarrow$	Subset of Pareto optimal points $X \in \boldsymbol{S}^o \subset \boldsymbol{S} \rightarrow$	Subset of Pareto optimal points, $X \in \boldsymbol{S}_q^o \subset \boldsymbol{S}^o \subset \boldsymbol{S} \rightarrow$	Separate point $\forall X \in \boldsymbol{S}\; X \in \boldsymbol{S}_q^o \subset \boldsymbol{S}^o \subset \boldsymbol{S}$

This is the most important result which allows constructing the principle of optimality and methods of choosing any point from a set of Pareto optimal points.

Definition 8. (*Principle of optimality 2. The solution of a vector problem with the set criterion priority*).

The vector problem of Eqs. (4.1)–(4.4) with the set priority of the q^{th} criterion of $p_k^q\lambda_k(X)$, $k=\overline{1,K}$, is considered solved if there is such a point X^o and such a maximum level λ^o found among all relative estimates that:

$$\lambda^o = \boldsymbol{max}_{X\in S}\boldsymbol{min}_{k\in K} p_k^q\lambda_k(X), q \in \boldsymbol{K}. \tag{5.15}$$

Using the interrelation of Eqs. (5.13) and (5.14), we can transform the maximin problem of Eq. (5.15) into an extreme problem of the form:

$$\lambda^o = \boldsymbol{max}_{X\in S}\lambda, \tag{5.16}$$

at restriction

$$\lambda \leq p_k^q\lambda_k(X), k=\overline{1,K}. \tag{5.17}$$

We call Eqs. (5.16) and (5.17) the λ-problem with a priority of the q^{th} criterion.

The solution of the λ-problem is the point $\boldsymbol{X}^o = \{X^o, \lambda^o\}$. This is also the result of the solution of the vector problem of Eqs. (4.1)–(4.4) with the set priority of the criterion, solved on the basis of normalization of criteria and the principle of the guaranteed result.

In the optimum solution $\boldsymbol{X}^o = \{X^o, \lambda^o\}$, X^o, an optimum point, and λ^o, the maximum lower level, the point of X^o and the λ^o level correspond to restrictions of Eq. (5.9), which can be written as:

$$\lambda^o \le p_k^q \lambda_k\left(X^o\right),\, k = \overline{1,K}.$$

These restrictions are the basis of an assessment of the correctness of the solution in the practical vector problems of optimization.

From Definitions 1 and 2, "Principles of optimality", follows the opportunity to formulate the concept of the operation "opt".

Definition 9. (*Mathematical operation "opt"*).

In the vector problem of Eqs. (4.1)–(4.4), in which "max" and "min" are part of the criteria, the mathematical operation "opt" consists in determining such a point X^o and such a maximum lower level λ^o in which all criteria are measured in relative units:

$$\lambda^o \le \lambda_k\left(X^o\right) = \frac{f_k\left(X\right) - f_k^0}{f_k^* - f_k^0},\, k = \overline{1,K}, \tag{5.18}$$

i.e., all criteria of $\lambda_k\left(X^o\right), k = \overline{1,K}$, are equal to or greater than the maximum level of λ^o (therefore λ^o is also called the guaranteed result).

Theorem 2. (The theorem of the most inconsistent criteria in a vector problem with the set priority).

If in the convex VPMP of Eqs. (4.1)–(4.4) the priority of the q^{th} criterion of $p_k^q, k = \overline{1,K}, \forall q \in \boldsymbol{K}$ over other criteria is set, at a point of an optimum $X^o \in \boldsymbol{S}$ obtained on the basis of normalization of criteria and the principle of guaranteed result, there will always be two criteria with the indices $r \in \boldsymbol{K}$, $t \in \boldsymbol{K}$, for which the following strict equality holds:

$$\lambda^o = p_k^r \lambda_r\left(X^o\right) = p_k^t \lambda_t\left(X^o\right),\, r,t \in \boldsymbol{K}, \tag{5.19}$$

and other criteria are defined by inequalities:

$$\lambda^o \le p_k^q\left(X^o\right),\, k = \overline{1,K},\, \forall q \in \boldsymbol{K},\, q \ne r \ne t. \tag{5.20}$$

Criteria with the indices $r \in \boldsymbol{K}$, $t \in \boldsymbol{K}$ for which the equality of Eq. (5.20) holds are called the most inconsistent.

Proof. Similar to Theorem 2 [7].

We note that in Eqs. (5.19) and (5.20), the indices of criteria r, $t \in \boldsymbol{K}$ can coincide with the $q \in \boldsymbol{K}$ index.

Consequence of Theorem 1, about equality of an optimum level and relative estimates in a vector problem with two criteria with a priority of one of them.

In a convex VPMP with two equivalent criteria, solved on the basis of normalization of criteria and the principle of the guaranteed result, at an optimum point X^o equality is always carried out at a priority of the first criterion over the second:

$$\lambda^o = \lambda_1\left(X^o\right) = p_2^1\left(X^o\right)\lambda_2\left(X^o\right),\, X^o \in \boldsymbol{S}, \tag{5.21}$$

where $p_2^1\left(X^o\right) = \lambda_1\left(X^o\right) / \lambda_2\left(X^o\right)$, and at a priority of the second criterion over the first:

$$\lambda^o = p_1^2\left(X^o\right)\lambda_1\left(X^o\right) = \lambda_2\left(X^o\right),\, X^o \in \boldsymbol{S},$$

where $p_1^2\left(X^o\right)=\lambda_2\left(X^o\right).\lambda_1\left(X^o\right)$.

5.3. Mathematical algorithm of the solution of a vector problem with equivalent criteria

To solve VPMP (4.1)–(4.4), we proposed the methods based on axioms of the normalization of criteria and the principle of the guaranteed result which follow from Axiom 1 and Principle of Optimality 1. We will present it in a number of steps:

Step 1. VPMP (3.1)–(3.4) is solved for each criterion separately, i.e. at the maximum for $\forall k \in \boldsymbol{K}_1$, and at the minimum for $\forall k \in \boldsymbol{K}_2$. As a result, we obtain:

X_k^* is an optimum point by the corresponding criterion, $k=\overline{1,K}$;

$f_k^*=f_k\left(X_k^*\right)$ is the value of the k^{th} criterion in this point, $k=\overline{1,K}$.

Step 2. We find the worst value of each criterion on $\boldsymbol{S}$: f_k^0, $k=\overline{1,K}$. For this purpose, we solve problem (4.1)–(4.4) for each criterion of $k=\overline{1,\boldsymbol{K}_1}$ at the minimum:

$$f_k^0=\min f_k\left(X\right), G\left(X\right)\le B, X\ge 0, k=\overline{1,\boldsymbol{K}_1}.$$

Problem (4.1)–(4.4) is solved for each criterion $k=\overline{1,\boldsymbol{K}_2}$ at the minimum:

$$f_k^0=\max f_k\left(X\right), G\left(X\right)\le B, X\ge 0, k=\overline{1,\boldsymbol{K}_2}.$$

As a result, we obtain: $X_k^0=\left\{x_j, j=\overline{1,N}\right\}$, which is an optimum point by the corresponding criterion, $k=\overline{1,K}$; $f_k^0=f_k\left(X_k^0\right)$, which the value of the k^{th} criterion in the point of X_k^0, $k=\overline{1,K}$.

Step 3. We perform a system analysis of a set of Pareto optimal points. For this purpose, in optimum points of $X^*=\left\{X_k^*, k=\overline{1,K}\right\}$ we determine the values of criterion functions of $F(X^*)$ and relative estimates $\lambda\left(X^*\right), \lambda_k\left(X\right)=\dfrac{f_k\left(X\right)-f_k^0}{f_k^*-f_k^0}, \forall k\in\boldsymbol{K}$:

$$\lambda_k\left(X\right)=\frac{f_k\left(X\right)-f_k^0}{f_k^*-f_k^0}, \forall k\in\boldsymbol{K}.$$

$$F\left(X^*\right)=\left\{f_k\left(X_k^*\right), q=\overline{1,K}, k=\overline{1,K}\right\}=\begin{vmatrix} f_1\left(X_1^*\right),\dots,f_K\left(X_1^*\right)\\ \dots\\ f_1\left(X_K^*\right),\dots,f_K\left(X_K^*\right)\end{vmatrix},$$

$$\lambda\left(X^*\right)=\left\{\lambda_q\left(X_k^*\right), q=\overline{1,K}, k=\overline{1,K}\right\}=\begin{vmatrix} \lambda_1\left(X_1^*\right),\dots,\lambda_K\left(X_1^*\right)\\ \dots\\ \lambda_1\left(X_K^*\right),\dots,\lambda_K\left(X_K^*\right)\end{vmatrix}. \quad (5.22)$$

In general, in VPMP, the relative $\forall k \in \boldsymbol{K}$ estimate of $\lambda_k\left(X\right), k=\overline{1,K}$ lies within $0\le\lambda_k\left(X\right)\le 1$, $k=\overline{1,K}$.

Step 4. Construction of the λ-problem.

The construction of the λ-problem is carried out in two stages:

Initially, we construct a maximin problem of optimization with the normalized criteria which at the second stage is transformed to the standard problem of mathematical programming called the λ-problem. For the construction of a maximin problem of optimization, we use definition 2:

$$\forall X \in \boldsymbol{S} \;\; \lambda = \boldsymbol{min}_{\boldsymbol{k} \in \boldsymbol{K}} \lambda_k \left(X\right).$$

The lower λ level is maximized with respect to $X \in S$, as a result we formulate a maximin problem of optimization with the normalized criteria.

$$\lambda^o = \boldsymbol{max}_{X \in \boldsymbol{S}} \boldsymbol{min}_{\boldsymbol{k} \in \boldsymbol{K}} \lambda_k \left(X\right). \tag{5.23}$$

At the second stage, we transform problem (5.23) into a standard problem of mathematical programming:

$$\lambda^o = \boldsymbol{max}_{X \in \boldsymbol{S}} \lambda, \quad \rightarrow \quad \lambda^o = \boldsymbol{max}_{X \in \boldsymbol{S}} \lambda, \tag{5.24}$$

$$\lambda - \lambda_k \left(X\right) \le 0,\, k = \overline{1,K}, \quad \rightarrow \quad \lambda - \frac{f_k\left(X\right) - f_k^0}{f_k^* - f_k^0} \le 0,\, k = \overline{1,K}, \tag{5.25}$$

$$G\left(X\right) \le B,\, X \ge 0, \quad \rightarrow \quad G\left(X\right) \le B,\, X \ge 0. \tag{5.26}$$

In λ-problem (5.24)–(5.26), the vector of unknown X has the dimension of $N + 1$: $X = \{X, x_1, ..., x_N\}$.

Step 5. Solution of λ-problem.

λ-problem (4.24)–(4.26) is a standard problem of convex programming and for its solution we use the standard methods.

As a result of solving λ-problem, we obtain: $\boldsymbol{X^o} = \{\boldsymbol{X^o}, \boldsymbol{\lambda^o}\}$ is an optimum point;

$f_k\left(X^o\right),\, k = \overline{1,K}$ are values of the criteria in this point;

$\lambda_k\left(X^o\right) = \dfrac{f_k\left(X\right) - f_k^0}{f_k^* - f_k^0},\, k = \overline{1,K}$ are values of relative estimates;

λ^o is the maximum relative estimate which is the maximum lower level for all relative estimates of $\lambda_k(X^o)$, or the guaranteed result in relative units. λ^o guarantees that all relative estimates of $\lambda_k(X^o)$ are greater than or equal to λ^o:

$$\lambda_k\left(X^o\right) \ge \lambda^o,\, k = \overline{1,K} \quad \text{or} \quad \boldsymbol{\lambda^o} \le \lambda_k\left(X^o\right),\, k = \overline{1,K},\, X^o \in \boldsymbol{S},$$

and according to Theorem 1 the $X^o = \{\boldsymbol{\lambda^o}, x_1, ..., x_N\}$ point is a Pareto optimum.

5.4. Mathematical method of the solution of a vector problem with criterion priority

Step 1. We solve a vector problem with equivalent criteria. The algorithm of the solution is presented in Section 5.3.

As a result, we obtain:

optimum points by each criterion separately $X_k^*,\, k = \overline{1,K}$ and values of criterion functions in these points of $f_k^* = f_k\left(X_k^*\right),\, k = \overline{1,K}$, which represent the boundary of a set of Pareto optimal points;

anti-optimum points by each criterion of $X_k^0 = \left\{x_j,\, j = \overline{1,N}\right\}$ and the worst unchangeable part of each criterion of $f_k^0 = f_k\left(X_k^0\right),\, k = \overline{1,K}$;

$\boldsymbol{X^o} = \{X^o, \lambda^o\}$, an optimum point, as a result of the solution of VPMP at equivalent criteria, i.e., the result of the solution of a maximin problem and the λ-problem constructed on its basis;

λ^o, the maximum relative estimate that is the maximum lower level for all relative estimates of $\lambda_k(X^o)$, or the guaranteed result in relative units, λ^o guarantees that all relative estimates of $\lambda_k(X^o)$ are equal to or greater than λ^o:

$$\lambda^o \le \lambda_k\left(X^o\right), k=\overline{1,K}, X^o \in S. \tag{5.27}$$

The decision-maker carries out the analysis of the results of the solution of the vector problem with equivalent criteria.

If the obtained results satisfy the decision-maker, then the process concludes, otherwise subsequent calculations are performed.

In addition, we calculate:

in each point $X_k^*, k=\overline{1,K}$ we determine values of all criteria of:

$q=\overline{1,K}\left\{f_q\left(X_k^*\right), q=\overline{1,K}\right\}, k=\overline{1,K},$ and relative estimates $\lambda\left(X^*\right)=\left\{\lambda_q\left(X_k^*\right), q=\overline{1,K},\right.$ $\left.k=\overline{1,K}\right\}, \lambda_k\left(X\right)=\dfrac{f_k\left(X\right)-f_k^0}{f_k^*-f_k^0}, \forall k\in \boldsymbol{K}:$

$$F\left(X^*\right)=\begin{vmatrix} f_1\left(X_1^*\right)\dots f_K\left(X_1^*\right)\\ \dots\\ f_1\left(X_K^*\right)\dots f_K\left(X_K^*\right)\end{vmatrix}, \lambda\left(X^*\right)=\begin{vmatrix} \lambda_1\left(X_1^*\right)\dots \lambda_K\left(X_1^*\right)\\ \dots\\ \lambda_1\left(X_K^*\right)\dots \lambda_K\left(X_K^*\right)\end{vmatrix}. \tag{5.28}$$

Matrices of criteria of $F(X^*)$ and relative estimates of $\lambda(X^*)$ show the values of each criterion of $k=\overline{1,K}$ upon transition from one optimum point $X_k^*, k\in \boldsymbol{K}$ to another $X_q^*, q\in \boldsymbol{K}$, i.e., on the border of a great number of Pareto.

at an optimum point at equivalent criteria X^o we calculate values of criteria and relative estimates:

$$f_k\left(X^o\right), k=\overline{1,K}; \lambda_k\left(X^o\right), \overline{1,K}, \tag{5.29}$$

which satisfy the inequality of Eq. (4.27). In other points $X \in \boldsymbol{S}^o$, in relative units the criteria of $\lambda = = \boldsymbol{min}_{k\in \boldsymbol{K}} \lambda_k(X)$ are always less than λ^o, given the λ-problem of Eqs. (5.24)–(5.26).

This information is also a basis for further study of the structure of a great number of Pareto.

Step 2. Choice of priority criterion of $q \in \boldsymbol{K}$.

We know from the theory (see Theorem 1) that at an optimum point X^o there are always two most inconsistent criteria, $q \in \boldsymbol{K}$ and $v \in \boldsymbol{K}$, for which an exact equality holds in relative units:

$\lambda^o = \lambda_q(X^o) = \lambda_v(X^o), q, v \in \boldsymbol{K}, X \in \boldsymbol{S}$. Others are subject to inequalities:

$$\lambda^o \le \lambda_k\left(X^o\right), \forall k\in \boldsymbol{K}, q\ne v\ne k.$$

As a rule, the criterion which the decision-maker would like to improve is part of this couple, and such a criterion is called a priority criterion, which we designate $q \in \boldsymbol{K}$.

Step 3. We determine numerical limits of the change in the value of the criterion priority $q \in \boldsymbol{K}$.

For priority criterion $q \in \boldsymbol{K}$, we use the matrix of Eq. (5.22) to determine the numerical limits of the change of the criterion value:

$$f_q\left(X^o\right)\le f_q\left(X\right)\le f_q\left(X_q^*\right), q\in \boldsymbol{K}, \tag{5.30}$$

where $f_q\left(X_q^*\right)$ derives from the matrix of Eq. (4.28) $F(X^*)$, all criteria showing values measured in physical units, $f_k\left(X^o\right), k=\overline{1,K}$ from Eq. (4.29), and, in relative units of

$$\lambda_q\left(X^o\right) \le \lambda_q\left(X\right) \le \lambda_q\left(X_q^*\right), q \in \boldsymbol{K}, \tag{5.31}$$

where $\lambda_q\left(X_q^*\right)$ derives from the matrix $\lambda(X^*)$, all criteria showing values measured in relative units (we note that $\lambda_q\left(X_q^*\right)=1$), $\lambda_q(X^o)$ from Eq. (5.22).

As a rule, Eqs. (5.30) and (5.31) are displayed for analysis.

Step 4. Choice of the value of priority criterion (decision-making).

The decision-maker carries out the analysis of the results of calculations of Eq. (5.28) and from the inequality of Eq. (5.30) chooses the numerical value f_q of the criterion of $q \in \boldsymbol{K}$:

$$f_q\left(X^o\right) \le f_q \le f_q\left(X_q^*\right), q \in \boldsymbol{K}. \tag{5.32}$$

For the chosen value of the criterion of f_q, it is necessary to determine a vector of unknown X^o. For this purpose, we carry out the subsequent calculations.

Step 5. Calculation of a relative estimate.

For the chosen value of the priority criterion of f_q, the relative estimate is calculated as:

$$\lambda_q = \frac{f_q - f_q^0}{f_q^* - f_q^0}, q \in \boldsymbol{K}, \tag{5.33}$$

which upon transition from point X^o to X_q^*, according to Eq. (5.27), lies in the limits:

$$\lambda_q\left(X^o\right) \le \lambda_q \le \lambda_q\left(X_q^*\right) = 1.$$

Step 6. Calculation of the coefficient of linear approximation.

Assuming a linear nature of the change of criterion of $f_q(X)$ in Eq. (5.30) and according to the relative estimate of $\lambda_q(X)$ in Eq. (5.31), using standard methods of linear approximation we calculate the proportionality coefficient between $\lambda_q(X^o)$, λ_q, which we will refer to as ρ:

$$\rho = \frac{\lambda_q - \lambda_q\left(X^o\right)}{\lambda_q^* - \lambda_q^0}, q \in \boldsymbol{K}.$$

Step 7. Calculation of coordinates of priority criterion with the value f_q.

In accordance with Eq. (5.32), the coordinates of the X^q priority criterion point lie within the following limits: $X^o \le X_q \le X_q^*, q \in \boldsymbol{K}$. Assuming a linear nature of change of the vector $X_q = \left\{x_1^q, ..., x_N^q\right\}$ we determine coordinates of a point of priority criterion with the value f_q with the relative estimate of Eq. (5.32):

$$X_q = \left\{x_1^q = x_1^o + \rho\left(x_q^*(1) - x_1^o\right), ..., x_N^q = x_N^o + \rho\left(x_q^*(N) - x_N^o\right)\right\},$$

where $X^o = \left\{x_1^o, ..., x_N^o\right\}$, $X_q^* = \left\{x_q^*(1), ..., x_q^*(N)\right\}$.

Step 8. Calculation of the main indicators of a point X_q.

For the obtained point x_q, we calculate:

all criteria in physical units $F^q = \left\{f_k\left(X_q\right), k = \overline{1, K}\right\}$,

all relative estimates of criteria

$$\lambda^q = \left\{\lambda_k^q, k = \overline{1,K}\right\}, \lambda_k\left(X_q\right) = \frac{f_k\left(X_q\right) - f_k^0}{f_k^* - f_k^0}, k = \overline{1,K},$$

the vector of priorities $P^q = \left\{ p_k^q = \frac{\lambda_q\left(X_q\right)}{\lambda_k\left(X_q\right)}, k = \overline{1,K} \right\}$,

the maximum relative estimate $\lambda^{oq} = \min\left(p_k^q \lambda_k\left(X_q\right), k = \overline{1,K}\right)$.

Any point from Pareto's set $\boldsymbol{X_t^o} = \left\{\lambda_t^o, X_t^o\right\} \in \boldsymbol{S^o}$ can be calculated in a similar way.

Analysis of results. The calculated value of criterion $f_q\left(X_t^o\right), q \in \boldsymbol{K}$ is usually not equal to the set f_q. The error of the choice of $\Delta f_q = \left|f_q\left(X_t^o\right) - f_q\right|$ is defined by the error of linear approximation.

Conclusion

Thus, the following results are obtained in the article.

1. The study and analysis of the management of the multi-level system of the state within the digital economy has shown that the activities of state authorities aimed at managing the economic and social development of the state include the relationship between the state, regions (subjects of the Russian Federation) and municipalities should be an integral part of the national policy of the state. We defined "Digital economy" and showed its use in the management of a multi-level system of the state.

2. We carried out an analysis of economic and mathematical models of the company's development and on its basis we developed the theoretical foundations of mathematical modeling of the development and management of an industrial enterprise: a cluster that represents the lower level of state management. We proposed a mathematical model of the functioning of an industrial enterprise (cluster), represented by a vector problem of mathematical programming. This model allows making an optimal decision considering a set of criteria (economic indicators) in the aggregate.

3. To solve the vector problem of mathematical programming, a mathematical apparatus based on the normalization of criteria and the principle of guaranteed results is presented. The presented mathematical modeling apparatus provides, first, an opportunity to solve one of the most important problems of the theory of the firm - making an optimal decision based on a certain set of economic indicators (criteria) in the aggregate, secondly, the numerical model of the enterprise allows you to assess the dynamics of production development, economic indicators, relative growth rates, and collectively assess the investment required for such production growth, and, thirdly, allows you to form a strategic plan for innovative development of the enterprise, taking into account extensive and intensive factors (technologies) of production development.

The direction of research related to the strategic development of the multi-level socio-economic system of the state in the digital economy creates a methodological basis for the development and implementation of management decisions focused on the priority areas of economic development of the state. In this direction, the structure of the multi-level hierarchical system of the state economy is developed, aimed at solving the problems of forecasting, strategic planning and management at individual levels of the state within the digital economy. To solve the problems of forecasting and planning, a mathematical apparatus based on the theory and methods of vector optimization has been developed. At the lower level of the hierarchical system of the state economy, a mathematical model of a corporation (cluster) is studied, which takes into account both extensive and intensive factors of production development. In the cluster model, the input data is, first, statistical information and, second, technological information of the production preparation. It is shown that in the aggregate, statistical, technological information, as well as the relationship with consumers of products and with the financial (banking) sphere, is characterized as "digital economy".

The direction of further research is related to the practical implementation of mathematical models, vector optimization methods and their use in the practice of forecasting, planning and development of all departments of the state and industrial corporations (clusters) in particular.

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RELATIONSHIP OF DIGITAL AND INDUSTRIAL ASPECTS IN ECONOMIC RESEARCH BASED ON ECONLIT BIBLIOMETRIC ANALYSIS

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The reviews of scientific economic literature show growing complexity of interrelationships between subject areas and discord among different types of publications, registered editions and subject classifications. In this context, the need to comprehend the digitalization trends is becoming more and more acute. This paper presents the results of bibliometric analysis of more than one and half million publications indexed in the electronic bibliographic EconLit database in terms of digital and industrial aspects and interrelation between them. The records, in which the title contains the terms "digital" or "digitization", "online", "smart", "mobile", "internet", "computer" or "computing", "telecommunication" and "software" were attributed to the "digital aspect". The publications of "industrial aspect" belong to 37 JEL micro categories of four-meso categories with the title of "Industry Studies" (L6 Manufacturing; L7 Primary Products and Construction; L8 Services; L9 Transportation and Utilities). The paper contains a set of indicators for assessment of the digitalization degree of publications reflected in EconLit in 1991–2020. These indicators help to discover the "points of growth" at the intersections of digital and industrial aspects in the research object and subject framework. The presented results showed that the world economic literature continues to pay more attention to the problems and methods of digitalization. Analysis of publication activity by sub-periods of 1991–2020 helped to single out four terms ("online", "digital", "smart", "mobile") with a pronounced increase in activity. Examples of some notable publications illustrate the most interesting trends. The highest values of "digitalization rates" are in the category L63 Microelectronics, computers, communications. The digitalization rates above average are in L8 Service, where the leader is L86 Information and Internet Services; Computer Software. L7 Primary Products and Construction is only making first steps towards digitalization. The thoughts about future research developments conclude the main section of the article.

Keywords: bibliometric analysis, digitalization, industry studies, publication activity, JEL classification, new research directions

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ВЗАИМОСВЯЗЬ ЦИФРОВОГО И ИНДУСТРИАЛЬНОГО АСПЕКТОВ В ЭКОНОМИЧЕСКИХ ИССЛЕДОВАНИЯХ С ПОЗИЦИИ БИБЛИОМЕТРИЧЕСКОГО АНАЛИЗА НА ОСНОВЕ ECONLIT

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Изучение научной экономической литературы показывает растущую сложность взаимосвязей между предметными областями и отсутствие необходимой согласованности между различными типами публикаций, зарегистрированными изданиями и предметными классификациями. На этом фоне становится все более острой потребность в понимании тенденций цифровизации. В данной статье представлены результаты библиометрического анализа более полутора миллионов публикаций, проиндексированных в электронной библиографической базе данных EconLit, с позиции цифрового и индустриального аспектов и взаимосвязи между ними. Записи, в названии которых содержатся термины «цифровой» или «цифровизация», «онлайн», «умный», «мобильный», «Интернет», «компьютер» или «компьютерные вычисления», «телекоммуникации» и «программное обеспечение» отнесены к «цифровому аспекту». В массив публикаций «индустриального аспекта» отнесены записи EconLit по тридцати семи JEL-микрокатегориям, которые, в свою очередь, входят в четыре мезокатегории с общим подзаголовком «Индустриальные исследования». В их числе: L6 «Обрабатывающая промышленность», L7 «Первичные продукты и строительство», L8 «Услуги», L9 «Транспорт и коммунальные услуги». В статье представлен набор показателей для оценки степени цифровизации публикаций, отраженных в EconLit в 1991–2020 гг. Эти индикаторы помогают обнаружить «точки роста» на пересечении цифровых и индустриальных аспектов в рамках объекта и предмета исследования. Полученные результаты показали, что в мировой экономической литературе продолжается уделяться все больше внимания проблемам и методам цифровизации. Анализ публикационной активности по подпериодам 1991–2020 годов позволил выделить четыре термина («онлайн», «цифровой», «умный», «мобильный») с выраженным ростом активности. Примеры некоторых примечательных публикаций иллюстрируют наиболее интересные тенденции. Наибольшие значения «темпа цифровизации» – у категории L63 «Микроэлектроника, компьютеры, связь». Показатели цифровизации выше среднего – в мезокатегории L8 «Услуги»: в ней лидером является микрокатегория L86 «Информационные и интернет услуги; программное обеспечение». Мезокатегория L7 «Первичные продукты и строительство» делает только первые шаги по пути цифровизации. Мысли о будущих направлениях исследований довершают основной текст статьи.

Ключевые слова: библиометрический анализ, цифровизация, индустриальные исследования, публикационная активность, классификация JEL, новые направления исследований

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Introduction

A word search in titles and other parts of the bibliographic description of foreign (Scopus, Web of Science, Google Scholar) and domestic (elibrary.ru) publications, conducted in March 2021, confirmed the main conclusion drawn in [1] and in a number of other studies. In recent years, we have been observing noticeable growth of research on digitalization (or the digital aspect) in general, and economics and management in particular. The number of publications in this area is constantly increasing. There is a growing complexity of interrelationships between subject areas and discord among different types of publications, registered editions and subject classifications. The need to comprehend the digitalization trends is becoming more and more acute.

The Scopus citation system uses the ASJC classification. It singles out two macro categories for economics and management out of 27 general categories. It presents 14 micro categories out of 334. At the same time, the economic editions worldwide apply the JEL subject classification. At the end of 2020, it had 859 micro categories. Electronic bibliography EconLit, in addition to books and articles in scientific journals, takes into account articles in collective volumes, PhD dissertations and working papers. In the latter, they provide new research directions at the intersections of subject categories. Because of these facts, the problem of monitoring the accumulated economic knowledge in various available databases and identifying emerging research areas using bibliometric analysis remains urgent.

The object of the research is publications in EconLit from January 1, 1991 to March 31, 2021 (hereinafter – the observation period) related to meso categories with the general subtitle "Industry Studies": L6 Manufacturing; L7 Primary Products and Construction; L8 Services; L9 Transportation and Utilities.

The subject of the research will be publications, in which the title contains the terms "digital" or "digitization", "online", "smart", "mobile", "internet", "computer" or "computing", "telecommunication" and "software". We will assume that publications with these terms relate to the "digital aspect" of economic research. If necessary, it is possible to expand the subject of research by searching the indicated keywords not only in the titles, but in other parts of EconLit records as well.

The purpose of the study is to assess and, if possible, to illustrate the relationships in time for 1991–2020 and in the space of JEL subject categories from the standpoint of the industrial and digital aspects within the framework defined by the object and subject of the research.

Three interrelated research tasks are the following:

1. To give an aggregated assessment of the publication dynamics for the terms of the "digital aspect" based on the total number of records in EconLit for three adjacent periods of 1991–2021.

2. To provide an aggregated assessment of the digitalization degree of publications reflected in EconLit for the observation period, for all JEL micro categories included in the meso categories L6, L7, L8 and L9.

3. To refine the findings based on the expansion of the object base with the digitalization examples of some notable publications.

Research methodology and database. The methodology is based on the concept of system-innovative bibliometric analysis and mapping of economic literature [2], which is detailed in an original combination of three methods: 1) terminological and lexical analysis, 2) determining the characteristics of publication activity, 3) structural-morphological analysis. The source of information was the online version of the EconLit electronic bibliography and its 1,501,620 records of all six types of publications. These publications date to the period from January 01, 1991 (the date of introduction of the new version of the JEL subject classification), and until March 31, 2021.

Detailing the methodology and the results of solving the first problem – an aggregated assessment of the dynamics of publications based on the selected digitalization terms out of the total number of records in EconLit. NP denotes the total number of records in EconLit for a certain period with corresponding specification in each case. Table 1 shows the results of sequential pairwise partitioning of the period 1991–2021 (as of 21.03.2021) so that the corresponding NP amounts are approximately equal and the growth rate (T) is close to unity. The letter N in the column designations indicates the number of records by periods that have the last two digits of the calendar year: N9108 – from 1991 to 2008, N0921 – from 2009 to 2021, N0914 – from 2009 to 2014, N1521 – from 2015 to 2021, N1517 – from 2015 to 2017, N1821 – from 2018 to 2021. The end years of the allocated periods are after the designation of the growth rate T.

For the digital term, the label "All" indicates the search results in all fields of the record. The label "TI" for "digital" as well as the terms in other lines concern the search results for the "term in the title".

The bold type highlights the cases when the rate of growth of the term frequency is above the average level showed in the NP line. We see that in the last decade in the world scientific literature, indexed in the authoritative electronic bibliographic EconLit database, the number of works marked with such explicit terms of the era of the digital economy as "online" and "digital" has grown most rapidly. Between these terms, the frequency of the term "smart", which modern smartphones and artificial intelligence works are closely related to, is also growing rapidly. The fast development of mobile service has found expression in absolute and relative volumes of the term "mobile".

We emphasize that the year 1991 is the starting point in Table 1, so there is consistency of calculations when solving research problems 1 and 2. Nevertheless, the conclusions will not fundamentally change if we take into account the small number of publications of the considered type published before 1991. The first work with the term “online” in the title appeared in 1982 [3]. Then we see only four publications until 1991. Taking this into account, T = 5.21. The word “smart” can be first spotted in relation to Scottish damask linen industry in 1963 [4], then there are 17 other works published until 1991 that leads to T = = 4.78. “Digital” in the title appears in 1968 [5], with seven additional publications afterwards, resulting in T = 2.53.

Table 1. Comparative analysis of aggregated publication activityby selected terms of the “digital aspect”

Term	N9108	N0921	T2108	N0914	N1521	T2114	N1517	N1821	T2117
NP	745,902	755,718	1.01	399,209	356,527	0.89	205,158	151,567	0.74
online	351	1,854	**5.28**	440	1,190	**2.70**	508	683	**1.34**
smart	202	1,052	**5.21**	1,360	3245	**2.39**	1,403	1,847	**1.32**
digital (all)	1,544	4,605	**2.98**	682	1,172	**1.72**	600	572	**0.95**
digital (TI)	636	1,630	**2.56**	340	712	**2.09**	362	351	**0.97**
mobile	616	1,418	**2.30**	689	729	**1.06**	383	347	**0.91**
internet	1,598	1,583	0.99	799	784	**0.98**	452	332	0.73
computing	378	344	0.91	351	203	0.58	136	67	0.49
software	763	554	0.73	191	165	0.86	103	62	0.60
computer	899	356	0.40	180	164	**0.91**	95	68	0.72
telecommunication	1,884	630	0.33	403	227	0.56	141	87	0.62

For the “All” case, the gain will be 12 units, and T = 2.96. The term “mobile” was in the scientific economic literature since 1963 in relation to “mobile homes” [6]. Until 1991, there were 58 such records in EconLit. This fact resulted to a slight decrease in the growth rate (2.1 versus 2.3). Since the term “internet” first appeared only in 1992 [7], this did not affect the results in Table 1. Starting with the term “computing”, there is a sharp increase in the number of publications with the analyzed terms until 1991 (marked by D90), and, accordingly, an even greater decrease in growth rates: computing [8] – D90 = 103, T = 0.72; software [9] – D90 = 130, T = 0.62; computer [10] – D90 = 557, T = 0.24; telecommunication [11] – D90 = 312, T = 0.29.

Detailing the methodology and the results of solving the second problem – assessing the degree of digitalization by micro categories included in the meso categories L6, L7, L8 and L9. As in the solution of the first research task, we extracted the Econlit data for two adjacent periods (1991–2008 and 2009–2021) and used the search variant “terms in the title”. The search covered all 37 micro categories included in meso categories L6, L7, L8, and L9 from the following list (the number in parentheses is the total number of records in 1991–2021):

Industry Studies (InSt): Manufacturing:

- L60 (18371) InSt: Manufacturing: General.
- L61 (3652) Metals and Metal Products; Cement; Glass; Ceramics.
- L62 (6896) Automobiles; Other Transportation Equipment; Related Parts and Equipment.
- L63 (4605) Microelectronics; Computers; Communications Equipment.
- L64 (2132) Other Machinery; Business Equipment; Armaments.
- L65 (7085) Chemicals; Rubber; Drugs; Biotechnology; Plastics.
- L66 (11168) Food; Beverages; Cosmetics; Tobacco; Wine and Spirits.
- L67 (3893) Other Consumer Nondurables: Clothing, Textiles, Shoes, and Leather Goods; Household Goods; Sports Equipment.
- L68 (955) Appliances; Furniture; Other Consumer Durables.
- L69 (286) InSt: Manufacturing: Other.

InSt: Primary Products and Construction (PP&C):
- L70 (657) InSt: PP&C: General.
- L71 (7358) Mining, Extraction, and Refining: Hydrocarbon Fuels.
- L72 (2542) Mining, Extraction, and Refining: Other Nonrenewable Resources.
- L73 (1341) Forest Products.
- L74 (1728) Construction.
- L78 (562) InSt: PP&C: Government Policy. L79 (5) InSt: PP&C: Other.

InSt: Services:
- L80 (3795) InSt: Services: General.
- L81 (10156) Retail and Wholesale Trade; e-Commerce.
- L82 (9335) Entertainment; Media.
- L83 (16049) Sports; Gambling; Restaurants; Recreation; Tourism.
- L84 (5680) Personal, Professional, and Business Services.
- L85 (830) Real Estate Services.
- L86 (9593) Information and Internet Services; Computer Software.
- L87 (705) Postal and Delivery Services.
- L88 (1835) InSt: Services: Government Policy.
- L89 (168) InSt: Services: Other.

InSt: Transportation and Utilities:
- L90 (719) InSt: Transportation and Utilities: General.
- L91 (1115) Transportation: General.
- L92 (12097) Railroads and Other Surface Transportation.
- L93 (4348) Air Transportation.
- L94 (13849) Electric Utilities.
- L95 (3141) Gas Utilities; Pipelines; Water Utilities.
- L96 (9613) Telecommunications.
- L97 (727) Utilities: General.
- L98 (12154) InSt: Utilities and Transportation: Government Policy.
- L99 (17) InSt: Utilities and Transportation: Other.

We used the following steps to calculate the indices in Tables 2 and 3.

1. We found the total record numbers for the first and second periods for each JEL code in the examination list.
2. We found the records with the terms of the “digital aspect” in the titles for the same periods and JEL codes.
3. We calculated the corresponding ratios for each term and JEL code (column DE) separately for the first period (K1) and the second period (K2) by means of dividing the frequencies of these terms by the number of records, in percent (Tables 2 and 3).

The data labeled with “digital” includes the terms “digital” and “digitalization”, and the data labeled with “computer” includes the terms “computer” and “computing”.

We distributed the columns with the term names in descending order of coefficients for the total number of records for the second period. Values that are greater than or equal to the overall average ratios given in the NP line are in bold.

There are no lines L69 in Table 2 and L99 in both Tables due to the lack of publications of the required type.

Unexpectedly, it turned out that the overwhelming majority of publications with codes from the L7 meso-region do not have any of the subject terms under consideration in their titles. Therefore, Tables 2 and 3 present the results only for meso categories L6, L8 and L9.

Table 2. Four terms of the "digital aspect" with increasing digitalization rates

DE	Online		Digital		Mobile		Smart	
	K1	K2	K1	K2	K1	K2	K1	K2
NP	0.05	0.25	0.09	0.23	0.08	0.19	0.03	0.14
L60	0.01	0.21	0.06	**0.31**	0	0.02	0	**0.23**
L61	0	0.09	0.07	0.09	0	0	0	0
L62	**0.14**	**0.38**	**0.1**	0.05	0	0.13	0.03	**0.35**
L63	**0.29**	**0.69**	**2.06**	**1.84**	**0.82**	**4.88**	**0.08**	**0.51**
L64	0	0	**0.24**	**0.23**	0	0	0	0.08
L65	0.06	0.19	0.03	0.03	0	0.03	0	0.06
L66	0	**0.27**	0	0.03	0.03	0.05	0.03	0.05
L67	0	**1.17**	**0.17**	0.05	0	0.05	0	0.09
L68	0	**0.53**	**0.26**	0.18	**0.51**	0.18	0	**1.07**
S	**0.06**	**0.32**	**0.27**	**0.25**	**0.09**	**0.35**	0.02	**0.19**
L80	**0.09**	**1.17**	**0.09**	**2.34**	0	0	0	
L81	**2.71**	**6.45**	**0.67**	**1.17**	**0.38**	**0.71**	**0.13**	0.06
L82	**0.83**	**2.36**	**3.64**	**3.97**	**0.46**	**0.95**	0	0
L83	**0.18**	**1.01**	0.04	0.17	**0.14**	0.1	0	0
L84	**0.43**	**0.62**	0.06	**0.47**	**0.49**	0.07	0	0
L85	0	0.23	0	**0.23**	0	0	0	0
L86	**1.79**	**7.18**	**4.28**	**6.80**	**0.73**	**3.18**	**0.12**	**0.69**
L87	**0.38**	**0.45**	**1.15**	**2.71**	0	0	0	0
L88	**1.08**	**1.87**	**8.5**	**2.50**	**0.18**	**1.79**	**0.18**	**0.16**
L89	**1.32**	0	**0.66**	0	0	0	0	0
S	**0.99**	**3.14**	**1.74**	**2.12**	**0.34**	**0.85**	**0.05**	**0.2**
L90	0	0	0	0	0	**0.4**	0	0
L91	0	**0.33**	0	**0.5**	0	0	0	0
L92	0	**0.26**	0	0.17	0.05	0.17	**0.03**	**0.37**
L93	**0.17**	**0.55**	0.06	0.08	0.06	0.16	**0.06**	**0.16**
L94	0	0.08	0	0.01	0.03	0.04	**0.03**	**1.71**
L95	0	0.05	0	0.05	0	0	0	**0.56**
L96	**0.22**	**0.43**	**2.06**	**2.88**	**6.11**	**19.55**	0.03	**0.43**
L97	0	0	**0.27**	0	0	0	0	**0.85**
L98	0	0.08	**0.91**	**0.58**	**2.05**	**3.05**	0	**1.18**
S	**0.08**	0.20	**0.54**	**0.31**	**2.03**	**2.80**	0.01	**0.56**

It is possible to consider the micro category L96 Telecommunications as a semantic indicator of the analysis, since only in it we see complete coincidence of the subject term and the name of the micro category. Considerable values of the K1 and K2 coefficients reflect this case. The number of tokens in the title in the second period decreased by 66%, which almost coincided with the overall decrease in the NP line amounting to 67%. The close link between the development of mobile communications and telecommunications services leads to a significant increase in K2 in the "mobile" column and in the L96 row.

Table 3. Four terms of the "digital aspect" with decreasing digitalization rates

DE	Internet		Telecommunication		Computer		Software	
	K1	K2	K1	K2	K1	K2	K1	K2
NP	0.25	0.21	0.25	0.08	0.17	0.09	0.1	0.07
L60	0.08	**0.21**	0.04	0.01	**0.23**	0.07	**0.13**	0
L61	0	0.09	0	0	0.14	**0.09**	0.07	0.04
L62	0.21	0.2	0.03	0.03	0.17	**0.1**	**0.1**	0.08
L63	**0.62**	**0.28**	**1.89**	0	**10.16**	**2.49**	**1.85**	0
L64	0.12	0.15	0	0	**0.36**	**0.23**	**0.24**	**0.08**
L65	0.09	0.06	0.03	0.06	0.11	**0.11**	0.09	**0.11**
L66	**0.27**	0.09	0	0	0.09	0.03	0.03	0.04
L67	0.23	0.19	0	0	0.06	0.05	0	0
L68	**0.26**	0.18	0	0	0	0.18	0	0
L69	**0.60**	**0.83**	0.6	0	**0.6**	0	**0.6**	0
S	0.19	0.16	0.21	0.01	**1.16**	**0.23**	**0.27**	0.03
L80	**0.41**	0	0.13	**0.17**	**0.22**	**0.17**	**0.13**	0
L81	**5.26**	**1.87**	0.06	0.03	0.16	0.06	0.03	**0.09**
L82	**1.69**	**1.54**	**0.55**	**0.23**	0.15	0.08	**0.18**	**0.13**
L83	**0.69**	**0.37**	0.02	0	0.14	0.05	0	0.02
L84	**0.36**	**0.35**	0	0.1	**0.18**	**0.2**	**0.43**	**0.15**
L85	**2.02**	**0.92**	**0.25**	0	**0.25**	**0.23**	0	0
L86	**16.93**	**15.82**	**1.77**	**0.4**	**3.39**	**1.88**	**9.12**	**7.28**
L87	0	**0.9**	**0.38**	**0.45**	0	0	0	0
L88	**7.05**	**7.96**	**2.17**	**0.47**	0	**0.47**	**1.08**	**0.55**
L89	**1.32**	0	**0.66**	0	**0.66**	0	0	0
S	**4.96**	**3.26**	**0.54**	**0.14**	**0.84**	**0.34**	**2.01**	**1.07**
L90	0	0	**4.24**	**0.4**	**0.64**	0	0	0
L91	0.19	0	**1.74**	0	0	0	0	0
L92	0.16	0.07	**0.45**	0.05	**0.24**	0.05	0.03	0
L93	**0.28**	**0.39**	**0.45**	0	**0.22**	**0.16**	0	0
L94	0.03	0.06	**0.43**	**0.15**	0.05	0.02	0	0.01
L95	0	0.1	**0.5**	0.05	0.08	0	0	0
L96	**5.83**	**4.85**	**29.08**	**15.36**	**0.58**	**0.24**	0.09	**0.24**
L97	0	**0.85**	**0.53**	**0.28**	0.00	**0.28**	0	0
L98	**1.9**	**0.65**	**17.22**	**4.05**	0.11	0.04	0	0
S	**1.52**	**0.69**	**11.46**	**2.56**	**0.26**	0.07	0.03	0.03

One of the innovations at the end of the XX century concerns the use of power line supports for fiber-optic communication lines. This has the reflection in the coefficients at the intersection of the "Telecommunications" column and the L94 Electric Utilities row.

One may consider Tables 2 and 3 as a kind of "maps of the sea of economic research". Cells with the number "0" are the "sea surface". As we move along the map, we come across the emerging "islands of digitalization", each with its own publications reflected in EconLit. Of course, a more detailed description of these sections requires a much larger volume (for example, as done in [12]).

Noteworthy is the "leap" of digitalization in the L60 category. Here you can find a "systematic literature review" under the intriguing title "Smart Factory as a Key Construction in Industry 4.0" [13].

For both periods and on average, the highest values of "digitalization rates" are in the category L63 Microelectronics, computers, communications. For it, the "online" and "smart" aspects are important. The related issues of innovation, knowledge integration and learning are also discussed [14]. We also see an increase in the coefficient of the L67 category, which includes "clothing, textiles, footwear, and leather goods". These products are subject to fashion, and for this, as stated in the article [15], it is necessary to "respond quickly" using "logistics Internet platforms", while not forgetting to use stochastic dynamic programming to optimize management decisions.

The analysis of the coefficients for the L65 category led to the article [16], the title of which begins with the question: "Is the Genie Out of the Bottle?" Although the article appeared in January 2019, its content (conducting clinical trials of drugs using digital platforms and social networks) takes on a new dimension during the pandemic. Article [17] in relation to the L68 micro category presents an interesting combination of the production of "green smart furniture" and the "innovative business model of the company" that deals with this production.

In the online column in the L8 Service section, we see a significant number of cells with digitalization rates above average. If we select the micro category L81 and the records from 2015 only, we find 305 entries. By topics, among them with the definition of online are the following: retailer (72), shopping (64), markets (39), order (21), offline (20), auctions (16), platforms (16), and customer (13). Adding the term "digital" to the title yielded one book with two words "marketing" in the title [18] and 4 journal articles. One abstract contains the following important statement for a correct understanding of digitalization: "automation will not replace lawyers, but will help them and make their work more efficient" [19].

Moving to micro category L82 yielded 82 entries since 2015 with topics corresponding to the name of the micro category: advertising (26), newspaper (7), online game (7), music (6), ratings (5), etc. Already at the level of publication titles, questions about the effectiveness of online advertising [20] and the usefulness of "following the crowd" [21] inevitably arise.

Micro category L86 Information and Internet Services; Computer Software, thanks to its subject, seems to "permeate" all columns in tables 2 and 3 with significant levels of digitalization. A sample of 1000 records with the L86 code for 2017–2021 shows the following initial frequency distribution of topics: digital (154), platform (76), software (76), social media (60), broadband (56), China (43), cyber, security (38), review (33), search, Google (32). For 2018–2021, we found 994 records, in which, in addition to the previous one, the topics mobile (65), economic growth (44) and digital economy (27) appeared. Of course, blockchain and digital currency were among the issues discussed [22].

The growing frequency of the term "smart" in category L94 Electric Utilities is of great interest. Among the 170 records, we see "smart meter" (57 entries), "smart grid technology" (10), "smart home" (8), "smart charging" (often together with "electric vehicles") (7). If we go to the total level of EconLit then we find 1273 records including different combination with the word "smart": city (220), grid (127), growth (118), specialization (85), metering (79), money (64), climate (51), energy (38), economics (32), card (31), home (27), market (20), innovation (15), policy (10).

We considered the problems brought up for discussion within the framework of the conferences INPROM and ECOPROM in the recent years and could not ignore the following findings: in one title "clusters teach to accelerate regional smart specialization" [23], "innovative regions" are considered from the position of "smart innovation policies" [24], and there is a "smart innovation ecosystem" [25].

Features of digitalization of research within the meso category L7 Primary Products and Construction. EconLit makes it possible to conduct a search both for the "micro category–term" pair using the search phrase **subjdesc: L70 title: digital**, and for the entire set of the studied terms that characterize the processes of digitalization of research at once. In this case, the phrase will be longer: **subjdesc: L70 title: digital OR title: digitization OR title: online OR title: smart OR title: mobile OR title: internet OR title: computer OR title: computing OR title: telecommunication OR title: software**.

If you remove the words **title**: in the above phrase, then EconLit displays the publications with the search term in all fields of record. The described search option for all terms and for micro categories of meso category L7 at once, conducted on April 1, 2021, gave the following results:

L70(4; 21). L71(10; 139). L72(3; 57). L73(3; 45). L74(13; 65). L78(1; 15).

In parentheses, the first number is the total number of publications containing the search terms in their titles; the second number is the search result in all fields of the record.

L70. Two of the four papers in the title search are working papers that explore developments in the US telecommunications industry in 1990s. A working paper published in 2014 considers the topic of Smart Cities in China. A digitalization term in an article dated 2020 can be found in the phrase “Online Citizen Participation” [26]. In other publications of this micro category, the digital aspect is associated with the use of computer modeling, as well as with the analysis of the development of telecommunications.

L71. Of the 10 publications found in the term-in-title variant, there are three units focused on software (2004, 2008 and 2018), three on smart (“smart economy” in 2016, “smart policy” in 2017, “smart sanctions” in 2020). We see “mobile offshore drilling” in [27], “cloud computing” in [28], “internet of things” in [29], and “online big data-driven oil consumption forecasting” in [30].

In the search option for all fields, the frequency distribution of terms turned out as follows: software (31), online (25), computer (25), internet (23), telecommunication (17), computing (12), smart (9), mobile (9), digital (5). A comparison with the data in Tables 2 and 3 indicates a slower digitalization of studies in comparison with other meso categories.

Among the works with the term “digital” in abstracts, we wish to highlight three articles. The first paper presents the “digital elevation model” for assessing the social contribution to the work of mines [31]. The second paper discusses the widespread use of “digital components” in complex systems for analyzing accidents at coalmines [32]. The third article concerns the search for answers to three calls to electric power industry (decarbonization, decentralization and digitalization) [33].

Similarly, it is possible to analyze in more details other publications that touch on digitalization issues, both in the remaining micro categories of the L7 meso category, and included in the L6, L8, and L9 meso categories.

General conclusions, discussion questions and possible research directions. The presented results of bibliometric analysis based on the EconLit electronic bibliography showed that the world economic literature continues to pay more attention to the problems and methods of digitalization.

This process is complex, and for a more complete understanding of it, it is necessary to use not only the term “digital” and its derivatives, but also other related terms reflecting the ongoing changes. We suggested one of the possible sets of such terms (digital or digitization, online, smart, mobile, internet, computer or computing, telecommunication and software). Analysis of publication activity by the sub-periods of 1991–2020 helped to single out four terms (online, digital, smart, mobile) with a pronounced increase in publication activity.

The JEL subject classification, in contrast to ASJC, makes it possible to assess the relationship between digital and industrial (by 37 micro categories) aspects of economic research with more details. This article is the first example (in the world literature) of such an assessment.

The obvious ambiguity of terminological and lexical analysis with the help of well-known bibliographies and electronic libraries is not only the choice of the terms themselves and their combinations, but also the choice of fields for search (by names, by names and keywords, etc.). This was especially evident in the analysis of micro categories of the meso category L7 Primary Products and Construction.

A possible direction for the development of the analysis can be a comparison of the results based on EconLit with the results of assessing the degree of digitalization of economic research based on the records from the Scopus database.

In all cases, we must not forget that bibliometric analysis, like any statistical or model study, presupposes addition from the side of meaningful analysis of both the texts of scientific publications and real economic problems.

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CREATING A NATIONAL CERTIFICATION SYSTEM FOR UNMANNED VEHICLES: TASKS OF INFORMATION SECURITY TESTING

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Currently, digital technologies are penetrating all spheres of public life and are rapidly changing the economic landscape of each country. The transport industry is actively introducing technical and organizational solutions related to the creation of self-driving cars and their safe operation. The transition to the widespread introduction of unmanned vehicles is associated not only with new opportunities for personal mobility and commercial logistics, but also with the emergence of new risks of using artificial intelligence technologies in vehicle traffic control and traffic regulation systems. In this regard this study is devoted to the creation of a procedure and mechanism for state certification of unmanned vehicles. The relevance of the study is determined by the characteristics of innovative solutions in this problem area and the high social value of ensuring transport security, including the protection of information interactions within the framework of intelligent transport systems. In the course of the study, the authors have given a definition of certification of information security of vehicles. The article discusses domestic and foreign experience in building certification systems for complex technical systems, including the assessment of means and mechanisms to ensure their safe operation. An analysis of the content and process of certification of unmanned vehicles was carried out from the standpoint of verifying compliance with information security requirements. The object, subject and goals of certification of unmanned vehicles are formulated. The work defines the composition and specificity of the tasks solved in the course of certification. The characteristics of the methods and procedure for certification of unmanned vehicles are given. The structure, regulations and mechanism for certification of unmanned vehicles have been determined. Based on the results of the study, the authors substantiated recommendations for improving the institutional framework and developing organizational solutions for creating a national certification system for unmanned vehicles. It also provides a characteristic of promising research tasks in the development of methodological support for the design of test platforms. The authors proposed a set of measures for creating planning tools and conducting tests to assess compliance with information security requirements for unmanned vehicles.

Keywords: unmanned vehicles, digital technologies, information security, threat modeling, testing profile, software certification, hardware certification, activity's licensing, state accreditation, economic model of certification

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ПОСТРОЕНИЕ НАЦИОНАЛЬНОЙ СИСТЕМЫ СЕРТИФИКАЦИИ БЕСПИЛОТНОГО АВТОТРАНСПОРТА: ЗАДАЧИ ТЕСТИРОВАНИЯ ИНФОРМАЦИОННОЙ БЕЗОПАСНОСТИ

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Цифровые технологии проникают во все сферы общественной жизни и стремительно меняют экономический ландшафт каждой страны. В транспортной отрасли активно создаются технические и организационные решения, связанные с созданием беспилотных транспортных средств и их безопасной эксплуатацией. Переход к широкому внедрению беспилотных автомобилей связан не только с новыми возможностями персональной мобильности и коммерческой логистики, но также и с возникновением новых рисков использования технологий искусственного интеллекта в системах управления движением автомобиля и регулирования транспортных потоков. В связи с этим настоящее исследование посвящено вопросам создания порядка и механизма государственной сертификации беспилотных автомобилей. Актуальность исследования определяется характеристикой инновационности решений в данной проблемной области и высоким социальным значением обеспечения транспортной безопасности, включая защиту информационных взаимодействий по различным каналам связи в рамках интеллектуальных транспортных систем. В ходе исследования авторами было дано определение сертификации информационной безопасности транспортного средств. В работе рассмотрен отечественный и зарубежный опыт построения систем сертификации сложных технических систем, включая оценку средств и механизмов обеспечения их безопасной эксплуатации. Был выполнен анализ содержания и процесса сертификации беспилотных автомобилей с позиций проверки обеспечения требований информационной безопасности. Сформулированы объект, предмет и цели сертификации беспилотных автомобилей. В работе определены состав и специфика решаемых в ходе сертификации задач. Дана характеристика методов и порядка сертификации беспилотных автомобилей. Определены структура, регламент и механизм сертификации беспилотных автомобилей. На основе результатов исследования авторами были обоснованы рекомендации по совершенствованию институциональной основы и разработке организационных решений для создания национальной системы сертификации беспилотных автомобилей. Также дана характеристика перспективных исследовательских задач в области разработки методического обеспечения проектирования тестовых платформ. Авторами предложен состав мер для создания инструментария планирования и проведения тестовых испытаний по оценке соблюдения требований информационной безопасности беспилотного автотранспорта.

Ключевые слова: беспилотный транспорт, цифровые технологии, информационная безопасность, моделирование угроз, профиль тестирования, сертификация программного обеспечения, сертификация технических средств, лицензирование, аккредитация, экономическая модель сертификации

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Introduction

Implementation of technological innovation projects becomes pivotal for creating necessary conditions for strategic tasks of the Russian Federation and achieving socio-economic development goals. This technological innovation will contour outlines of the national economic complex of the country. Transportation is one of the areas for perspective technical solutions deployment. Introduction of digital technologies leads to deep transformations of traffic management systems, and, as it is often the case with innovations, is associated with the emergence of new risks for unmanned vehicles safety.

The object of the present research is the transportation system of the Russian Federation. The subject of the research is developing a framework for information security service certification which is used for smart digital traffic management. The main goal of the study is to determine the key principles and tasks of creating a national certification system for unmanned vehicles. These tasks are linked to the technical solutions and organizational aspects for the development of testing grounds for information security level of tech platforms integrating an unmanned vehicle and road infrastructure. The tech platforms are created and introduced to the market of transportation services.

Caused by the general issue of ensuring road safety and the reasoning of state regulation of the technological development of the transport system, the main tasks of the study are to analyze existing approaches to ensuring the security of information interaction of connected and autonomous vehicles with active components of an intelligent transport system infrastructure (the so-called technological platform: Vehicle-to-Everything or V2X); to assess the impact of unmanned vehicle technologies on the socio-economic development of the country and determine the content and specifics of certification of unmanned vehicles from the standpoint of verifying information security requirements; to define the object, subject and purposes of unmanned vehicles certification; to typify the tasks, methods and procedures for certification of unmanned vehicles; to define structure, regulations and mechanism of the certification procedure for unmanned vehicles; to develop recommendations for improving the institutional framework and management procedures as a basis of establishing a national certification system for unmanned vehicles and the V2X technology platform used for building an intelligent transport system on a city, regional and national scale.

Vision of the future transport system with digital technologies employed

The creation of unmanned vehicles for land, air and water transport is one of the leading trends in scientific and technological development, which largely determines the future shape of the knowledge-based economy [1]. The development of unmanned vehicles (UVs) for various purposes is of great economic and social importance as a field of innovations that combine a number of advanced scientific approaches and technical solutions (from the so-called key end-to-end technologies of the new industrial wave: big data, artificial intelligence, wireless communication, internet of things, etc.). The functions of driver support (drive assist), partial automation and conditional automation when driving personal and commercial vehicles have become standard for 1, 2 and 3 classes of UV as per the SAE International classification system that is generally accepted in the professional environment. Experts state the further expansion of digital technologies to support production and organizational processes of road transportation in urban, intercity and main road traffic, assessing the transition from the emerging 4 UV class (limited automation) to the 5 UV class (full automation) after 2025 (https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety).

The transportation industry is of key importance for the integration of the entire economic complex of the Russian Federation spatial structure due to its vast territories. It shapes the opportunities for establishing convenient international transport corridors with multimodal transportation as well [2]. While it is too early to talk about a full-fledged market of autonomous vehicles (only some regions allowed limited operation of prototypes of UVs within certain sections of public-access roads), it is important to prevent the growth of the relative lag of the Russian Federation in the field of developing intelligent transport systems (ITS) and developing hardware and software complexes for automatic driving systems (IDS)[1]. Today the basics are being laid to establish the mechanisms for the distribution of a kind of technological rent in the field of passenger traffic and cargo traffic, that are optimized at the national and international levels of the economy, taking into account the evolution of the technical base of the transport industry and the restructuring of demand for transport services.

Catching up development: from import substitution to technological leadership

The transformation of the geopolitical and geoeconomic systems has caused appearance of the mechanism of unilateral restrictions in international relations as a tool of unfair competition to restrain economic and technological development in the segmented world of the renewed project of globalization. This leads to establishing of a "safety net" in the system of global affairs and cooperation[2] in various fields to minimize the risks of successful implementation of national projects in the internal agenda of dynamic and sustainable socio-economic development (SED) of the Russian Federation.

Therefore, the issues of deploying highly automated vehicles in the Russian Federation, including unmanned vehicles, should be the focus of the state's attention. It will contribute to the safe use of imported and localized technical devices (and corresponding technological protocols, standards and regulations) for intelligent transport systems. Moreover, it would be also beneficial to the establishing of sustainable demand for domestic analogues of hardware components[3] for computer and communication equipment which is crucial for critical information infrastructure facilities [3]. In the latter case, the obvious consequence will be the active recovery of domestic microelectronics by means of employing the strengths of the Russian science and engineering schools in the development of analytical, algorithmic methodology and software for the core of an automatic vehicle control system and a traffic control system with the participation of autonomous and connected vehicles.

In modern conditions, the implementation of technical and organizational innovations portfolio is linked with the emergence of new aspects of ensuring national security in the development and application of digital technologies. A significant part of it is associated with the use of foreign solutions and components for information-communication systems and hardware-software complexes for various purposes. In this regard, Russian science and business should be focused on and stimulated to develop original technologies and establish their own production of the entire range of components for UV and ITS, taking into account the advanced experience of foreign manufacturers. It is noteworthy that in the case of analysis of imported software and devices (components and finished products), we are talking about the aspects of assessing compliance with national requirements and regulations of products and technologies already prepared for practical use with a preliminary assessment of their economic efficiency and commercial potential. In this case, the strategy consists in leading domestic developers towards the implementation of the catch-up development opportunities. Firstly, they ensure the total costs reduction within the life cycle of tested products and technologies. And secondly, they provide concentration of resources on innovative projects in certain areas with a relative competitive advantage of the

[1] In ITS smart roads ecosystem includes solutions for collecting and processing data on vehicles and road infrastructure for decision-making by road users, including operators of connected and autonomous vehicles: adaptive (smart) traffic lights; means of automatic recording of violations of traffic rules (SDA); monitoring systems for difficult road sections; electronic means of non-stop fare payment; electronic means of payment for parking (parking meters); connected information boards; traffic flow detectors; automatic weight and dimensional control systems; automated lighting control systems; GPS / GLONASS positioning systems; other connected objects, for example, automatic road weather stations, road controllers, travel stops (barriers), etc.

[2] The well-known concept was reformulated in a statement by the Minister of Foreign Affairs of the Russian Federation S.V. Lavrov, who commented on September 13, 2020, in the information and analytical program of the All-Russian State Television and Radio Broadcasting Company (VGRTK), the situation with the EU's actual refusal to implement its own strategic interests in the development of mutually beneficial economic integration (see: https://www.vesti.ru/article/2457436).

[3] New technical solutions for the national ITS ecosystem should be created in accordance with the requirements of the Federal Law "On the Security of the Critical Information Infrastructure of the Russian Federation" dated July 26, 2017 No. 187-FZ and the order of the Government of the Russian Federation dated January 17, 2020 No. 20-r "On the Strategy for the Development of the Electronic Industry of the Russian Federation for the Period up to 2030 and the Action Plan for its Implementation". In particular, the roadmap currently being developed for the project "New Generations of Microelectronics and the Creation of an Electronic Component Base" provides for financing of work in the amount of 798 billion rubles until 2024 (see: https://www.cnews.ru/news/top/2020-09-07_rossijskaya_mikroelektronika).

national scientific and engineering schools. The design, production and operation of the UV requires a thorough analysis and comprehensive accounting for emerging risks in the field of ensuring the safety of transport communications. When creating control systems for a vehicle and developing intelligent complexes for traffic regulation, the safety of road traffic in the context of an expanding range of digital technologies used is linked, first of all, with ensuring the protection of information interaction of the UV with the road infrastructure (RI), i.e. cybersecurity of the V2X (Vehicle-to-Everything) technological platform within the ITS [4].

Thus, along with direct state support for research and technical development in the field of autonomous vehicles, it is important to use institutional and organizational measures to regulate the emerging technology sector for highly automated vehicles, including proactive arrangements of conditions for the efficiency and competitiveness of technical solutions for autonomous vehicles in future national transport system vision. In the context of the international competition in the field of high-tech, the dominant country (countries) use protectionist measures to protect their leadership[4]. Under such circumstances, the lagging state, along with legal, but not very effective for ensuring national interests, retaliatory sanctions actions, which are caused by external illegal unilateral restrictions, has a completely legal and rather effective instrument for regulating the sphere of technological cooperation for the purpose of sustainable SED: the Institute for Certification of Products and Services. It is important that its application is carried out from the standpoint of ensuring the safety of using ITS components and technologies for the life and health of consumers.

Certification as a tool to support technological development

Certification, which emerged as a protection tool, has evolved into a complex toolkit, which has especially fully revealed its functionality in the digital environment of network forms of agent relationships in the field of end-user protection, the economic partnerships establishing, as well as the support and regulation of national technical / technological development [5, 6, 7, 8, etc.]. Certification as a state control tool is a legitimate way to reduce the exclusive offer of imported goods and increase the export potential of the goods of similar / interchangeable categories. The institute of certification solves the issue of ensuring the price and non-price competitiveness of the domestic industry in the state internal and foreign markets for high-tech complex products: requirements and restrictions simultaneously play the role of technological and antimonopoly regulation. The certification allows the use of state control on functional properties, quality characteristics and safety of products and technologies as a basis for: evaluation of the modern scientific and technical level; assessment of the sensitivity of the requirements of national standards and technological regulations; identification of the prospects for the localization of production; correction of the national research and development program.

Safety requirements for products / services are a universal way of organizing and implementing the homologation[5] of imported equipment (and technologies, if we consider the procurement of industrial equipment) of the UVs for the purpose of the following localization of the production of components / products. This creates the basis for the further restoration and establishing necessary engineering-technical and production-technological competencies centers with developing corresponding industry clusters in the national economy. Thus, certification of products / services will indirectly contribute to over-

[4] Of course, now this leadership of the so-called developed countries of the outgoing technological generation is de facto extremely unstable, taking into account both the growth rates of new world centers of economic power and scientific and technical competencies, and the specific properties of common knowledge as a commodity in the networked global economy. However, this instability is also the reason the developed countries are taking comprehensive measures to carefully protect their leadership positions in accordance with the commercial interests of transnational corporations, which have a highly concentrated and well-functioning legal and organizational mechanism for controlling industrial assets and financial flows.

[5] Homologation – bringing the technical characteristics of a product in line with the standards of the importing country in the certification process [9, 10, 11, etc.]. This general term defines the scope of tasks and the content of the process of determining the degree of suitability of communication equipment and assessing its compliance with national requirements (regional / local, if we are talking about operation in territories with special modes of economic activity, including nature reserves). The necessary checks usually consist in comprehensive testing, including checking the technical condition diagnostic systems, analyzing the signaling systems for operating modes and malfunctions, evaluating various aspects of operational safety, characterizing electromagnetic compatibility, etc.

coming the negative consequences of the process of restrictions on equal cooperation and on exports associated with the revival of "bloc thinking" in the "developed" countries and the use of tools of competition in the spheres of economic development and political containment of "unwanted" countries, especially in the framework of the trade turnover of components, equipment and double-purpose technologies, which are widely represented in the control complexes of UV. Of course, first of all, in order to overcome strategic gaps and technological backwardness, it is necessary to support national projects of scientific research and technical development (including joint ones), but it is equally important to create legal foundations and organizational mechanisms for ensuring scientific and technological development. The institute for certification of products and services (more broadly, technological platforms) can play a special role here. Obviously, as for controlled penetration of foreign products and technologies, and for the development of own research and production base for the effective use of the certification institute in regulating the domestic UVs market, it is important to timely design and correct the content of national technological standards and regulations. At the same time, a kind of general mechanism of coercion to innovations is being developed: state measures to accelerate and regulate technological development corridors are associated with financing the establishment of uniform regulatory requirements and standard technical solutions. It is also true for the ITS sphere, where integration is possible only on the basis of a common digital platform (the principle of interoperability and scalability in the escalation of relevant investment projects at the international, national, federal, regional and municipal levels).

Thus, in the field of development and application of digital UV technologies, it is required to implement a set of state measures to support technological and organizational innovations, including the development of a regulatory framework and technical solutions, an organizational mechanism and an economic model for a certification system in the market for testing devices and technologies to provide a cybersecurity technological platform (TP) of the interaction of the UV with the DI when establishing the rules and procedures for the accreditation of operators of the following services.

Object, subject and purposes of certification

Under the expansion of digital technologies and the increasingly complex electronic communications environment, cybersecurity is the most dynamically developing and critically important area for the global connectivity of all spheres of society, including economic activity in an unmanned environment. The security of autonomous and connected vehicles allowed to special and public roads must be properly established for the range of possible information threats of the regular operation of automatic driving systems and interaction with active and passive components of the road infrastructure. Certification (from lat. "Certum" – right, "facere" – to do) is a procedure carried out by the authorized body to confirm the compliance of the inspected objects with the established requirements of technical regulations and the provisions of national standards in the form of issuing a following certificate (in order to certify operational safety and application characteristics). The certification mode can be voluntary (professional certification) and mandatory (state certification). TP UV-DI cybersecurity certification based on the results of testing (analysis, assessment, validation, verification) refers to the sensitive area of ensuring personal and public data and safety, therefore, it should be mandatory for all ITS equipment market participants, UV for various purposes and transport services provided on the basis of UV.

Regarding the ITS, the object of UV cybersecurity certification is a wheeled vehicle[6] with installed electronic equipment and software for automation systems for driving a car in a traffic stream and systems for information interaction with other road users and elements of road infrastructure. During the audit, the subject of certification is to identify the individual characteristics of the cybersecurity of the evaluated UV, analyze how these characteristics match with the declared parameters of the UV developer / manufacturer, and determine the degree of stability of the UV cybersecurity maintenance system in

[6] An alternative wording is electronic equipment and software installed on a wheeled vehicle to automate the driving control of a car in a traffic stream and systems for information interaction with other road users and elements of the road infrastructure of an intelligent transport system.

the implementation of various scenarios of threats to information interaction between the UV and the ID of urban and main roads. In the process of mandatory testing of digital communications security, the aim of certification is to determine the degree of compliance of the V2X technological platform of the tested UV with the requirements of the national cybersecurity standard) for connected and autonomous vehicles with a driving automation class higher than 3.

Interaction mechanism of an autonomous vehicle with physical and cyber-physical infrastructure is established by the complex use of the following key enabling technologies of smart mobility: a) automation; b) digital user interface; c) information interconnectivity; d) digital data. Each of these technologies has its own profile of risks associated with accidental and intent violation of normal operation mode (use), which must be identified and assessed when certifying the object of analysis of the UV cybersecurity. National certification system for UV cybersecurity should be based on proven approaches for general model of an automated driving system specification, a model of threats from external sources for TP V2X specification and a threat assessment method that are used for assessment and testing during the design and development of a vehicle in accordance with the generally accepted V-type procedure for analyzing safety [12, 13, 14, 15, 16, etc.].

We propose the guidelines for testing the UV cybersecurity for the assessment of the criticality of threats to an automatic (automated) driving system:

- evidentiality, i.e. identification of threats that could be carried out during an attack in real conditions, confirmed by actual cases of attacks with an assessment of the final proof for making a decision on the need for correction (protection method);
- concreteness, i.e. defining clear elements and operations for use in the valuation method;
- operationality, i.e. formation of a workable (practical) procedure for identifying threats that can be established with a focus on the critical path of events leading to serious problems for the safe operation of a highly automated vehicle, to determine the possibility in the process of vehicle development to decide on the composition and priority of measures to protect automated driving system functions.

Analysis of existing approaches (see [17, 18, 19, etc.]) shows that to build a testing model and to ground the verification methodology, it is necessary to proceed from the following approximate composition of active threats of deliberate violation of the UV cybersecurity contour:

1) Vulnerability in the telematics communication unit (TCU) that could be exploited to allow a third party to remotely control the vehicle's TCU or to get access to the electronic control unit (ECU).

2) Vulnerability in the vehicle's entertainment system, which can be exploited by a third party remotely: to determine the location of the vehicle and then switch to the vehicle's remote control mode by invading the vehicle's built-in system from an exploited port of the cellular network and falsifying the controller firmware; unlock the doors of the vehicle by sending a command from the telematics server that is potentially dangerous for road users; to get access to confidential information on the operation of the car: leakage of information about the user ID and password can be used to activate the service settings of control systems; to gain access to confidential information on the operation of the vehicle: leakage of information about the user ID and password can be used to activate the service settings of control systems, etc.

3) Vulnerability in a wireless LAN that could be exploited to allow a third party to remotely control an unmanned vehicle by directing the user to an attacking site using a fake Wi-Fi hotspot or over a public cellular network.

4) Vulnerability in a mobile application that can be exploited to allow a third party to remotely control the settings of the human machine interface (HMI), air conditioner, burglar alarms and other devices via a Wi-Fi access point (DSRC) in a connected or offline car.

5) Vulnerability in a connected service, which can be exploited to allow a third party remotely: to conduct false authentication and control other vehicles during authentication between smartphones and the server API of the user (owner / operator) of the UV; to unlock and open the doors by gaining

access to the UV when the security token used to authenticate smartphone devices expires; enter an unintentional code from a USB port inside the car to distort the autonomous vehicle navigation (AVN) settings, etc.

Let us characterize the problem area and the available testing tools for UVs cybersecurity, determined by the specifics of the main parameters of the V2X technological platform within the ITS.

Objectives, methods and order of certification

The common task of the verification and validation methods for UV solutions is to obtain confirmation that the automated driving system tested for compliance with safety requirements ensures a positive balance of risks in comparison with the characteristics of a human driver, taking into account all possible driving scenarios arising from a noticeable external influence. It is assumed that full testing of each individual threat scenario is not appropriate and technically feasible, therefore an acceptable and practical way to demonstrate / confirm the security of a system is based on a statistical assessment method. And although the experience of the commercial operation of the UV is still insufficient (there are examples of local use in the field of public transport), the accumulated material of laboratory and field tests and experimental operation in limited urban spaces allows us to formulate critical provisions for characterizing the profile of the cybersecurity threats of the UV [20, 21, 22, etc.], as well as even standardize the basic requirements for normative values and methods for assessing cybersecurity during research and certification tests of UV [12, 23, 24, etc.].

For example, in [25], representing the so-called "white paper" in the format used, specialists and experts from leading companies[7] in the intelligent vehicle market formulated an integrated approach to the consideration of topics and problems of automated driving safety, an overview of the basic elements and methods of ensuring the safety of high automated vehicle, as well as the characteristics of the methods of testing the safety[8] of technologies and devices of the UV. Let us characterize the key points of the provisions and recommendations that allow, according to expert estimates, to build, test and operate a safe automated vehicle. When carrying out certification for a UV with automation level 3 and higher, the following main challenges and tasks of security testing can be formulated, which make it possible to identify the degree of compliance of the tested device (object) with the established requirements:

– Objective 1. Statistical demonstration of the system's safety and positive balance of risks without interaction with the driver / operator: here it cannot be assumed that the driver / operator is fully alerted and involved in all scenarios, which implies the need to include statistical justifications in the general reasoning for the safety of the automatic driving system;

– Objective 2. System safety in interaction with the driver / operator (especially when switching / intercepting control maneuvers): the driver / operator must maintain awareness of the mode and receive an unambiguous indication of any mode transitions, and the system must reasonably maintain an effective interception ability to maintain controllability, which defines the requirement to analyze the effects of control interception on the safety of automatic driving;

– Objective 3. Consideration of currently unknown scenarios in traffic: new scenarios are a result of the emergence in a common network environment of risks of situations associated with the operation of a single automated traffic control system, and with interactions between individual automated driving systems and vulnerable road users traffic, which makes it mandatory to test the safety of automatic driving due to changes in the real and virtual world of the road infrastructure (situation);

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[7] The companies: Aptiv, Audi, Baidu, BMW, Continental, Daimler, FCA US LLC, HERE, Infineon, Intel and Volkswagen. They constitute the widest and most competent representation in the field of technology and system development, as well as in the production of components and devices for creating BPA.

[8] The focus here is on the development of security components and methods that are required to complement the long-standing and successful commercialized SAE Level 1 (Driver Assistance, DA) and Level 2 (Partial Automation, PA) automation systems. It is important to note that when characterizing SAE Level 3 and higher automated steering systems, the review authors consider the safety of a connected and autonomous vehicle in an electronic communications network environment in two aspects: as security, if it concerns active threats (factors of influence and impact of a predominantly digital environment), and as safety, if it concerns passive threats (factors of influence and impact of a predominantly physical environment).

– Objective 4. Verification of various configurations and variants of the system: since the automatic driving system consists of several elements, it is possible for various reasons (including deliberate unauthorized actions) to arise situations of asynchronous software updates and / or changes in equipment, which implies the need to test increased the number of options for the actual state of settings for assessing the safety of the automatic driving system;

– Objective 5. Validation of systems and subsystems based on machine learning: the functioning of the elements of automated vehicles of the next generations relies on machine learning algorithms when making control / regulatory decisions (for example, recognizing the traffic situation and evaluating actions), therefore, when assessing various impacts on them decomposition into individual components is unacceptable, which requires adapting methods for testing the overall safety of the automatic driving system.

An exemplary set of testing techniques is recommended in ISO 26262: 2018 "Road Vehicles – Functional safety" [26], which is the basis of the current draft international standard (DIS) of the detailed cybersecurity standard for ISU ISO / SAE DIS 21434 "Road Vehicles – Cybersecurity engineering" [27]. Test development methods are classified according to the degree of knowledge about the object under test (OuT). Obviously, the already characterized variability in the control settings and behavior / operation parameters of the FUA level 3 and higher in the digital environment of information communications corresponds to the recommendation specified in ISO 26262. The test design methods are based on:

– scheme-based test design techniques;
– equivalence partitioning test design techniques;
– value test design techniques;
– search-based test design techniques;
– design of experiments;
– mutation test design technique;
– reactive test design technique.

Testing of a UV in the process of its certification (as well as in the process of its design / development), depending on the specific design of the automated driving system, can be carried out with different testing purposes, which predetermines the combination of several test platforms for: a) different stages / areas of verification: individual components – functionality and reliability; integration of automatic driving systems components – static; UV systems in state control – static; UV systems in motion control – dynamic; system of external and internal communications BPA – human-machine interface; UV systems in the active environment of DI ITS; b) various test conditions: laboratories (software in loop, SiL; hardware in loop, HiL; driver in loop, DiL); closed polygon; open road.

Thus, checking the compliance of an intelligent vehicle with the cybersecurity requirements of the used TP UV-DI is a multi-level and multi-stage process. However, within the framework of state control, testing strategies with an emphasis on the entire automatic driving system should be used for mandatory verification of the safety level of the developed or operated UV as a whole.

It is obvious that the necessary technical base and professional competencies for certification can be organizationally and geographically distributed, which predetermines the need to optimize the structure of the construction and regulation of the functioning of the national certification system for BPA.

Structure, regulations and certification mechanism

The goals and functions of certification determine the structure of the national certification system: the state certification body for UV (with subdivisions of the federal, regional and local levels of authority and responsibility); accredited certification bodies, accredited testing laboratories. The subject and object of certification determine the inspection procedure: the conformity assessment procedure – declarative; types of tests performed – selective (components and devices) and complete (products and complexes), prototypes and serial products; types of official documents on the assessment of the characteristics of the cybersecurity of UV – test report, preliminary conclusion and certificate of conformity. The tasks and methods of certification determine the verification mechanism: the testing scheme should provide for both sanctions (manufacturer / importer: certification for the admission of UV and individual components of the automatic driving system to the UV market, first introduced to the consumer market and in the field of commercial / official transport services, including maintenance and repair of components vulnerable from the point of view of cybersecurity), and periodic inspection control (owner / operator: confirmation of the safety of products that have already passed the certification procedure and are allowed to operate – similar to the procedure for regular state technical inspection of vehicles for their admission to operation and the conclusion of appropriate insurance obligations).

The basic principle of building a certification system and conducting any certification tests is the independence of the testing laboratory, which conducts testing, and the certifying organization, which further monitors the results of the tests carried out by the laboratory. At the same time, the state certification body carries out a regular external audit[9] of the activities of the certifying organization and testing laboratories, assessing the completeness and quality of their functions, which, if gross and / or systematic violations are detected, may lead to the suspension and revocation of licenses, and the cancellation of accreditation certificates.

To fully reveal the ITS potential and effectively counteract the emerging cybersecurity threats, it is necessary to clearly and strictly coordinate the activities of all actors in the design and development, production and operation of BPA. The problems they face are complex, therefore, on the part of the state, certain efforts are required to concentrate professional competencies when developing the institutional framework for certification activities in the field of UV, as well as organizing the training of qualified specialists and creating a technical base for operators of the regulatory mechanism of this market.

It is obvious that the UV cybersecurity entirely depends on the competence and responsibility of the subject conducting the tests. It is important that the existing capabilities of domestic engineering centers, research laboratories and test sites are used to create a network of testing laboratories for the national certification system. The key tasks, in our opinion, are:

– determination of requirements for the operator of the certification services market (critical parameters: availability of competent personnel, availability and condition of test platforms for assessing the characteristics of equipment (hardware, HW) and programs (software, SW) for ITS from the standpoint of compliance with the characteristics of UV cybersecurity;

– development of a procedure for accreditation / certification of authorized certification organizations and testing laboratories: the use of a state control tool in the field of cybersecurity ITS is important for regular monitoring of the competence and equipment of market participants in the certification of UV;

– substantiation of the economic model of the UV certification process: the tariffs for certification and testing services should be determined differentially based on the type of UV, TP parameters of the information and communication interaction between the UV and the ID and the market capacity for the tested type of UV, as well as depend on the set of tests performed (coverage of current costs) and applied test platforms (covering investment costs for the necessary periodic modernization of test platforms and maintaining a high technical level of the tools for assessing compliance with the requirements of UV and ITS cybersecurity in connection with the rapid pace of innovation in the IT sphere).

Of course, the considered aspects of UV certification do not cover all issues of ensuring cybersecurity in the ITS environment and do not provide an exhaustive description of the problem of testing compliance with TP UV-DI. However, the arguments and formulated provisions can be used to justify organizational decisions and form the basic requirements of technological regulations for assessing condition and control of UV admission to operation on public roads.

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[9] In addition, the state certification body, in the event of incidents at the facilities, requests from consumers of certification services, or receiving requests from law enforcement agencies in accordance with the established procedure, related to the leakage of confidential and sensitive information about applicants and certification objects, may inspect certification organizations and testing laboratories.

Results, conclusions and recommendations

The study made it possible to identify the key problems and formulate the main issues of building a national cybersecurity certification institute within the framework of the ITS being created with the expanding scope of application of unmanned vehicles.

From our point of view, the complex of works to create a certification system for UV within the framework of ITS should include the following areas: improving the legal base for the verification and validation of systems and technologies for ITS; developing the functionality of the state certification agency and its territorial infrastructure; creation of a mechanism for licensing, accreditation and certification of participants in the testing process; organization of design, development and production of national software-hardware complexes for test platforms evaluating the level of cybersecurity of V2X technologies.

There are two approaches in the legal field of Russian legislation that are used to certify cybersecurity tools in the field of ITS based on the corresponding types of regulatory documents:

– Functional testing of UV identifying the fact of implementation of the declared functions by the checked object (product-product or technology) of the ITS. This testing is most often carried out for compliance with a specific regulatory document[10] – technological regulations. In some cases, in the absence of a document establishing the regulatory characteristics for cybersecurity for a certified object, the necessary functional requirements are formulated in the form of technical conditions or technical specifications (in accordance with the provisions of the GOST R 15408 standard).

– Structural testing of the program code used in the UV (HW and SW automatic driving systems and digital communications), which determines the absence of undeclared capabilities. That is, there is an identification of software tabs which initiate the performance of functions that are not declared and not described in the documentation to the components / devices of the UV upon the occurrence of certain conditions or when external authorization is carried out, which allows unauthorized influences on the monitoring and control information and, therefore, on the operating modes of the UV (in accordance with the provisions of the standard GOST R 51275-99).

The general organization of the certification process in accordance with common approaches and established practices in the regulatory area can be as follows:

1. The applicant submits an application to the federal / territorial certification agency for certification tests of the UV cybersecurity (component of automatic driving systems and digital communications).
2. The state certification agency determines the accredited certifying organization and testing laboratory for testing the UV cybersecurity.
3. The testing laboratory together with the applicant determines the testing plan[11].
4. The certifying organization and the applicant enter into a contract for the provision of certification services based on the agreed composition and cost of certification work.
5. The testing laboratory, as a co-contractor of the contract, conducts certification tests of selected product samples provided by the applicant in accordance with the selection rules for a full range of test and assessment works to confirm compliance with the UV cybersecurity requirements, including identification and analysis of documents submitted by the applicant.

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[10] For instance, the Federal Service for Technical and Export Control of the Russian Federation (until 2004, the State Technical Commission of Russia) established such guidelines for firewalls and means of protection against unauthorized access (see: https://fstec.ru/tekhnicheskaya-zashchita-informatsii/dokumenty/114-spetsialnye-normativnye-dokumenty/383-). In addition, for commercial software products, one can note the requirements for source code security auditing contained in the international standards PA DSS, PCI DSS and NISTIR 4909 (see: https://www.aadyasecurity.com/what-is-security-compliance- and-why-should-you-care).

[11] The test plan based on the accepted application includes the main certification conditions: certification scheme; regulatory documents on the basis of which certification will be carried out; information about the expert organization that will analyze the state of production, if provided by the certification scheme; the procedure for selecting samples of components / products for testing; the procedure for testing samples of components / products; the procedure for assessing the conditions for the production of components / products and the characteristics of information security of the developed (prototype) or operated (industrial design) BPA; criteria for assessing the compliance of UV cybersecurity with the requirements of technological regulations (state standard); the procedure for providing, if necessary, additional documents confirming the safety of components / products that are used in the BPA for operation in the environment of the national ITS.

6. On the basis of the protocols with the test results the testing laboratory prepares: a) preliminary conclusions on conformity (during a separate stage or one of the full cycles of cybersecurity testing), if certain inconsistencies with the established / declared requirements are revealed, which can be eliminated by the applicant in the course of work; b) the final conclusion (upon completion of the work plan for testing the object of verification provided by the applicant).

7. Test materials are transferred to the federal / territorial certification agency for an independent examination of the results of testing the UV cybersecurity (independent examination is carried out with the participation of at least two licensed expert organizations, which must confirm both the completeness and correctness of the tests, and the validity of the formulated conclusions and recommendations).

8. On the basis of the conclusion of the certifying organization within the established regulatory period (for example, 30 days) the state certification agency: draws up a certificate of conformity for the test object; organizes, in case of revealing any potentially removable inconsistencies, an additional examination with a change in the composition of the involved accredited certification organizations and testing laboratories; decides on the refusal to issue a certificate, providing the applicant with an act of work performed and a conclusion with justification of the identified discrepancies of the UV (components / products of automatic driving systems and digital communications) in terms of cybersecurity.

The transition to mass industrial and personal use of UV and the creation of a national certification system for assessing cybersecurity for TP UV-DI presupposes an introduction of significant changes and extensions of Russian legislation, including the correction of certain norms of the civil, administrative and criminal codices of the Russian Federation. First of all, we point out that in accordance with the provisions of Article 25 of the Federal Law No. 184-FZ “On Technical Regulation” dated 27.12.2002 (as amended on November 28, 2018), the equipment used and the services provided in this sphere should be included in the Unified list of products subject to mandatory certification[12], they require mandatory confirmation of compliance with the established safety requirements and quality characteristics should as determined in the technological operating regulations.

Here, it is important to ensure interdepartmental and inter-organizational interaction in the field of standardization of the development and operation of UV. It should be noted that the general functions of accreditation are concentrated in the Rosaccreditation[13] of the Ministry of Economic Development of the Russian Federation, which currently has 6 territorial agencies in federal districts. Taking into account the specifics of the task of assessing the vulnerabilities of information interaction within the TP UV-DI, it is necessary to choose an organizational form of cooperation between the Ministry of Transport of the Russian Federation (Federal Service for Supervision in Transport, Rostransnadzor) and the Ministry of Internal Affairs of the Russian Federation (State Inspectorate for Road Safety, Traffic Safety Inspectorate) with authorized state agencies in the field of cybersecurity: the Federal Security Service of the Russian Federation (Center for Licensing, Certification and Protection of State Secrets, CLCPSS FSB of Russia) and the Ministry of Defense of the Russian Federation (Federal Service for Technical and Export Control, FSTEC of the Ministry of Defense of Russia), which have the necessary powers and capabilities to assess the compliance of inspected objects with cybersecurity requirements. The main forms and mechanisms of certification for most of the cybersecurity means (SIS) and software

[12] Decree of the Government of the Russian Federation No. 982 “On approval of the unified list of products subject to mandatory certification and the unified list of products, the conformity of which is confirmed in the form of a declaration of conformity” dated 01.12.2009 (revised on July 4, 2020).

[13] The Federal Service for Accreditation (Rosaccreditation) is a federal executive organization performing the functions of the national accreditation body of the Russian Federation. Rosaccreditation was established in 2011 in accordance with the Decree of the President of the Russian Federation dated 24.01.2011 No. 86 "On the Unified National Accreditation System" and operates on the basis of the Regulations on the Federal Accreditation Service, approved by the decree of the Government of the Russian Federation "On the Federal Accreditation Service" dated 17.10.2011 No. 845 (revised on 23.03.2020). Rosaccreditation is administered by the Ministry of Economic Development of the Russian Federation. The sphere of activity of Rosaccreditation is: formation of a unified national accreditation system; control over the activities of accredited persons. In addition to information security tools, FSTEC also checks IT systems that store personal data: servers and networks of companies or cloud storages. This verification procedure is called the attestation of IT systems, carried out in accordance with the standards of the security levels of the Federal Law "On Personal Data" dated 27.07.2006, No. 152-FZ (revised on 20.04.2020).

are the certification systems for the CLCPSS of the FSB of Russia and the FSTEC of the Ministry of Defense of Russia. The FSB (CLCPSS) certification is intended for testing software subsystems that use cryptographic protection (in the Russian Federation, only national crypto protection algorithms are allowed). The requirements of the FSB certification systems are not public; familiarization with them requires special approvals. The MO (FSTEC) certification is intended to verify the technical protection of information by non-cryptographic methods. The requirements of the FSTEC certification system are open and published on the official website.

The policy in the field of accreditation of certifying organizations and testing laboratories for checking the requirements and certification of TP AV-DI should be determined with the participation of specialized units of the Ministry of Transport of the Russian Federation (Department of State Policy in the Field of Automobile and Urban Passenger Transport, Department of State Policy in the Field of Road Facilities, Department of Transport security and special programs), as well as taking into account the experience and specifics of functioning in the digital environment of traffic management centers (TMS) of public legal entities of the Russian Federation, in the territories of which the infrastructure of the national ITS will be deployed. For the organization of testing of the TP UV-DI cybersecurity, the existing experience of work on certification of technical devices of ensuring transport security in terms of technical devices / systems of inspection and intelligent video surveillance, used during the regular state technical inspection of vehicles, can be used. On March 30, 2017, the Decree of the Government of the Russian Federation No. 969 "On approval of the requirements for the functional properties of technical devices providing transport security and the Rules for mandatory certification of technical devices providing transport security" dated 26.09.2016 came into force, in accordance with which mandatory certification of technical devices providing transport security within the framework of periodic inspection of the condition of wheeled vehicles for various purposes, general requirements for them have been established, and the responsibility for their certification is assigned to the FSB of Russia. It is reasonable to assume that with the expansion of the scope of certification in the field of ITS, the accreditation of certifying organizations and testing laboratories for testing UV cybersecurity can also be entrusted to the CLCPSS FSB of Russia.

Conclusion

Expanding the range of automated functions or systems in vehicles has become a general trend in the use of modern advances in science and technology. While the original primary motivation was to make driving easier and the ride more comfortable, the next steps to automate driving are already focused on reducing fuel consumption and environmental impact, while improving driving safety. At the same time, it is obvious that automated driving and autonomous vehicle movement is a very difficult control task, therefore, replacing a human driver with a computer is a real problem from a technical, organizational and legal point of view.

Due to the emergence of new electronic components, the increased complexity of on-board electronic devices for automated driving and digital communications, the widespread use of intelligent technologies for automated traffic control and the rich information interaction of the vehicle with the external road environment, the safety of transport systems is affected in two ways. On the one hand, machine vision and artificial intelligence technologies can reduce the risks of road accidents involving UV. On the other hand, the range of threats associated with a possible violation of the functional integrity and operability of the UV due to intentional impacts on the electronic components of the automated driving system of the vehicle and its information and communication interaction with the road infrastructure, including traffic control centers within the ITS, is expanding.

This requires improvement of the norms and requirements of the legal and technical regulation of the creation and operation of connected and automated vehicles (CAVs) for various purposes on sections of roads of local and common use, which implies the expansion of the scope and tasks of testing the safety of public, personal, commercial and special vehicles, including by checking cybersecurity during validation and verification of devices / technologies of the UV and ITS components.

From the standpoint of integrated security in the development of unmanned vehicles for various environments (ground, air and water), it is essential to build a national certification system for systems and technologies ensuring the security of a technological platform for information interaction of UV with the surrounding infrastructure of the organization of automated (connected and autonomous) traffic in digital environment.

The issues discussed in this article make it possible to reveal the importance of the national certification system for ITS components and technologies both from the standpoint of ensuring road safety and digital sovereignty of the Russian Federation in the global network of automotive communications. This includes supporting projects for the restoration of national microelectronics through the formation of sustainable demand for electronic and element base for technical solutions of critical information infrastructure in one of the large-scale and significant sectors of the Russian economy. One of the most important areas for further research and development, in our opinion, should be the improvement of the methodological support for the design of test platforms for control of the safety of UVs for test sites and laboratories, as well as the development of comprehensive testing tools for assessing compliance with the cybersecurity requirements of unmanned vehicles in various modes / operation conditions [27, 28, 29, 30, etc.]. This will make it possible not only to ensure an approximation to the best world practices and trends in the development of end-to-end technologies for unmanned vehicles and the creation of a national mechanism to support innovation [31], but also make the formation of intelligent transport systems in the context of the digital transformation of society an effective and safe means of optimizing and accelerating logistics processes in solving strategic problems of sustainable socio-economic development of the Russian Federation.

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THE ROLE OF STRUCTURAL CHANGES IN THE MODERNIZATION OF THE ECONOMY

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In order to increase the competitiveness of the national economy, it is necessary to modernize and diversify the branches of the real sector. At the same time, the process of diversification and modernization of the economy and the structural transformation will be accompanied by a parallel interconnection. Ultimately, these two interconnected processes ensure transition to innovative development. In the country with innovative development, the export potential will be increased and sustainable economic growth will be ensured through the production of high value-added products. This, in turn, increases the national wealth and ensures the competitiveness of the national economy. The competitiveness of the national economy guarantees the welfare of the population. Through the implementation of the national economy modernization and structural transformation program in the world practice, many developed countries have ensured sustainable economic growth based on innovative factors. In this regard, Japan, Germany, the Republic of Korea and the People's Republic of China have achieved steady economic growth thanks to the deep structural transformation of the economy on the basis of economic modernization strategies. Modernization includes the technical and technological renewal of the leading sectors of the economy, the qualitative improvement, and ultimately, diversification of production, as well as the development of human factor. In the context of modernization of the national economy, it is crucial to form a state-of-the-art innovation program, to prepare a new generation of personnel effectively using innovations and investments and preparing a new class of investors. For this purpose, Uzbekistan needs a national idea for national technological development and domestic market modernization. This program should allow Uzbekistan to facilitate its inclusion into the list of the world's most developed countries. From this point of view, the formation of an innovation program, training of the new generation, effectively using innovations and investments, support for the development of a class of owners, become important. This requires a well-thought-out program for the technological development of Uzbekistan and the modernization of the domestic market. The implementation of this program should create new opportunities for Uzbekistan to find a worthy place in the ranks of the developed countries. In achieving these long-term strategic goals, the modernization of the national economy and the implementation of structural transformations play a leading role. The Strategy of Actions for the Development of the Republic of Uzbekistan for 2017—2021 has highlighted that "enhancing its competitiveness through deepening structural transformation, modernization and diversification of leading sectors of the national economy" is a priority.

Keywords: modernization, modernization of economy, investments, national economy, structural changes, priorities

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РОЛЬ СТРУКТУРНЫХ ИЗМЕНЕНИЙ В МОДЕРНИЗАЦИИ ЭКОНОМИКИ

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Для повышения конкурентоспособности национальной экономики необходимо модернизировать и диверсифицировать отрасли реального сектора. В то же время процесс диверсификации экономики с ее модернизацией и структурной трансформацией будет сопровождаться параллельной взаимосвязью. В конечном итоге эти два взаимосвязанных процесса обеспечивают переход к инновационному развитию. В стране с инновационным развитием экспортный потенциал будет увеличен, а устойчивый экономический рост будет обеспечен за счет производства продукции с высокой добавленной стоимостью. Это, в свою очередь, увеличивает национальное богатство и обеспечивает конкурентоспособность национальной экономики. Конкурентоспособность национальной экономики – залог благополучия населения. Реализуя в мировой практике программу модернизации национальной экономики и структурных преобразований, многие развитые страны обеспечили устойчивый экономический рост, основанный на инновационных факторах. В этом отношении Япония, Германия, Республика Корея и Китайская Народная Республика достигли устойчивого экономического роста благодаря глубокой структурной трансформации экономики на основе стратегий экономической модернизации. Модернизация включает техническое и технологическое обновление ведущих секторов экономики, качественное улучшение и, в конечном итоге, диверсификацию производства, а также развитие человеческого фактора. В контексте модернизации национальной экономики «крайне важно сформировать современную инновационную программу, подготовить новое поколение кадров, которые эффективно используют инновации и инвестиции и готовят новый класс инвесторов. Ведь для этого Узбекистану нужна национальная идея национального развития, развития технологий и модернизации внутреннего рынка, которая должна позволить Узбекистану ускорить доступ к наиболее развитым странам мира. С этой точки зрения важным становится формирование инновационной программы, обучение нового поколения, эффективное использование инноваций и инвестиций, поддержка развития класса собственников. Для этого нужна продуманная программа технологического развития Узбекистана и модернизации внутреннего рынка. Реализация этой программы должна создать для Узбекистана новые возможности занять достойное место в ряде развитых стран мира. В достижении этих долгосрочных стратегических целей ведущую роль играют модернизация национальной экономики и проведение структурных преобразований. В Стратегии действий по развитию Республики Узбекистан на 2017–2021 годы подчеркивается, что приоритетной задачей является «повышение ее конкурентоспособности за счет углубления структурных преобразований, модернизации и диверсификации ведущих секторов национальной экономики».

Ключевые слова: модернизация, модернизация экономики, инвестиции, национальная экономика, структурные изменения, приоритеты

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Introduction

In order to increase the competitiveness of the national economy, it is necessary to modernize and diversify the branches of the real sector. At the same time, the process of diversification and modernization of the economy and the structural transformation will be accompanied by a parallel interconnection. Ultimately, these two interconnected processes ensure transition to innovative development. In the country with innovative development, the export potential will be increased and sustainable economic growth will be ensured through the production of high value-added products. This, in turn, increases the national wealth and ensures the competitiveness of the national economy. The competitiveness of the national economy guarantees the welfare of the population.

Through the implementation of the national economy modernization and structural transformation program in the world practice, many developed countries have ensured sustainable economic growth based on innovative factors. In this regard, Japan, Germany, the Republic of Korea and the People's Republic of China have achieved steady economic growth thanks to the deep structural transformation of the economy on the basis of economic modernization strategies. Modernization includes the technical and technological renewal of the leading sectors of the economy, the qualitative improvement, and ultimately, diversification of production, as well as the development of human factor.

In the context of modernization of the national economy, it is crucial to form a state-of-the-art innovation program, to prepare a new generation of personnel effectively using innovations and investments and preparing a new class of investors. For this purpose, Uzbekistan needs a national idea for national technological development and domestic market modernization. This program should allow Uzbekistan to facilitate its inclusion into the list of the world's most developed countries[1].

From this point of view, the formation of an innovation program, training of the new generation, effectively using innovations and investments, support for the development of a class of owners become important. This requires a well-thought-out program for the technological development of Uzbekistan and the modernization of the domestic market. The implementation of this program should create new opportunities for Uzbekistan to find a worthy place in the ranks of the developed countries.

In achieving these long-term strategic goals, the modernization of the national economy and the implementation of structural transformations play a leading role. The Strategy of Actions for the Development of the Republic of Uzbekistan for 2017–2021 has highlighted that "enhancing its competitiveness through deepening structural transformation, modernization and diversification of leading sectors of the national economy"[2] is a priority.

Purpose of the study. Analyze the role of structural transformations in the process of modernization of the national economy of the country.

Research methods. In the process of the research, the structural method, systemic approach and grouping, comparative analysis, historical and logical method, scientific abstraction method and other methods were used.

Results and Discussion

The world practice shows that energy- and capital-intensive production with high specific consumption and a lack of integration of modern technologies in the national economy have a negative impact on product competitiveness. The opportunity to identify priorities of stirring Uzbekistan to the path of innovation will be facilitated through deep analysis of the conceptual aspects of accelerating the modernization processes in the economy and implementing structural changes. In the global economy, research is under way to establish a balance between the modernization of the economy and the structural changes.

In the process of formation of market relations in transitional economies, in most cases the concepts of "reform" and "transit economy" have been used instead of modernization theories. However, a single market institute was unable to ensure successful economic development, and the concepts of "modernization", "structural changes" and "national competitiveness" were introduced into the economic turnover. Modernization has begun to be regarded as a national program, not as a follow-up to the West [2, p. 40–52].

In 1960, Walt Whitman Rostow, an American scientist and Professor of the Massachusetts Institute of Technology, proposed a theory of transformation to the "self-sustaining growth" which had a great impact on the shaping of the concepts of modernization of the economies of the developed Western countries. The main idea of this theory is to transform a traditional society into a modern western society [4, p. 154–186],

[1] Mirziyoyev Sh.M. Address of the President of the Republic of Uzbekistan Sh. Mirziyoyev to the Oliy Majlis//www.president.uz

[2] Decree of the President of the Republic of Uzbekistan "About the strategy of action for the further development of the Republic of Uzbekistan" February 7, 2017, UP-4947//lex.uz

and the scientist improved his views of "self-sustaining growth" with subsequent economic growth stages [5, pp. 307–331]. Professor U. Rostow highlighted the following stages of economic growth:

1. Traditional society;
2. The preconditions for take-off;
3. The take-off;
4. The drive to maturity;
5. The age of high mass-consumption.

Let us briefly describe each of the above steps in terms of the modernization of the economy in Uzbekistan. According to the theory of U. Rostow, more than 75 percent of the population of the traditional economy is employed in agricultural production or processing, while the land resources are owned by private owners or the state. Note that according to the statistics of sectoral distribution, between 2000 and 2017, 12.7–13.5% of the population in Uzbekistan has been engaged in the industrial sector, while the share of the population employed in agriculture and forestry amounted to 34.4–27.3%, being significantly higher than in other sectors. It can be seen that the share of the employees in the industrial sector increased insignificantly, for example, in 2000, 1145 thousand people were in the industrial sector, and by 2017 the number increased up to 1825.2 thousand people. In agriculture and forestry, in 2000, 3093 thousand people were employed, and by the end of 2017 3691 thousand people[3] worked in the same sector.

Despite the fact that the agrarian sector generated more than 19.2% of the country's GDP, in 2017, investments in this sector accounted for only 3.3% of the total amount [14]. Thus, on the one hand, the increasing share of the manufacturing industry in the structure of GDP seems to be as a sufficient precondition for the transition to the next stage of economic development. On the other hand, the share of the economically active population employed in the agricultural sector in comparison with the other sectors explicitly shows that the economy remains at the stage of the traditional society.

The second stage, called "The preconditions for take-off", implies significant structural changes in the three non-industrial sectors: agriculture, transport and foreign trade. In the economy of Uzbekistan, the volume of agricultural production in 2000–2017 increased by 103.1–102.0% compared to the previous period, while the foreign trade turnover increased by 97.9–111.0% in the same period.

The Strategy of Actions for further development of Uzbekistan in 2017–2021 includes the construction of Bukhara-Miskin railway line in 2017, electrification of Karshi–Termez railway line in 2017 and Pop-Namangan-Andijan in 2017–2019 within the framework of improving the road condition and development of road infrastructure, electrification of the railway line, reconstruction of railways.

The third "Take-off" phase has lasted from 20 to 30 years, with growth rates of capital investment going up rapidly, the per capita output increases, and the introduction of new technologies in the industry and agriculture will accelerate. If the development first occurs in certain sectors, then the entire economy will be covered.

The fact that the share of fixed capital investments in gross domestic product is less than 24% ensures the rapid implementation of structural changes and modernization of the economy[4]. The world practice shows that the investment rate for modernization of the economy should be at least 25 percent.

If investment in fixed capital per capita in 2010 amounted to 543.4 thousand soms in the Republic of Uzbekistan, then in 2019 it amounted to 5834.6 thousand soms, and by the end of 2020 it was 5900.9 thousand soms. If we analyze this indicator in 14 regions (Table 1), it is higher than in the Republic of Karakalpakstan, Andijan, Jizzakh, Namangan, Samarkand, Surkhandarya, Syrdarya, Tashkent regions and Tashkent city in 2020.

Table 1 shows, that the per capita investment in 2020 increased by almost 11 times compared to 2010. The Kashkadarya, Bukhara and Navoi, which are the regions of large territory, have the potential to boost this figure.

[3] Cer.uz
[4] Cer.uz

Table 1. Investments into fixed capital per capita in 2010-2020 (in thousand sums)

Years / Regions name	2010	2015	2016	2017	2018	2019	2020	Change in 2020 compared to 2010
The Republic of Uzbekistan	543.4	1431.7	1608.6	2227.8	3769.6	5834.6	5900.9	10.9 t
The Republic of Karakalpakstan	279.5	3388.2	2094.0	1542.2	3641.1	4644.4	4273.7	15.3 t
Andijan	214.8	678.4	745.3	999.6	1550.3	2406.0	2772.4	12.9 t
Bukhara	1273.5	2264.0	3237.6	6254.2	5112.4	5429.3	5812.1	4.6 t
Jizzakh	319.5	1033.1	1125.1	1361.9	2693.9	5778.9	9291.9	29.0 t
Kashkadarya	639.7	1969.9	2389.3	3583.4	5193.4	7534.6	6032.2	9.4 t
Navoi	1987.6	1965.1	3168.1	4185.4	10892.1	17855.2	15954.9	8.0 t
Namangan	237.1	863.8	1074.8	1340.3	2992.5	4344.1	4220.5	17.8 t
Samarkand	296.8	912.0	1001.6	1189.4	1878.3	2674.9	3431.7	11.6 t
Surkhandarya	271.9	773.0	879.1	1427.1	2848.3	4552.8	3737.3	13.7 t
Syrdarya	532.3	1382.2	1660.3	2011.1	3280.2	7002.9	8404.0	15,8 t
Tashkent	581.4	1595.0	1507.5	2087.2	3898.4	6970.0	6399.9	11.0 t
Fergana	273.8	731.6	747.8	822.4	1516.8	2336.2	2990.0	10.9 t
Khorezm	227.0	884.7	885.8	1215.1	1655.6	2718.4	3544.6	15.6 t
Tashkent city	1472.4	2877.4	3848.1	5552.7	10627.8	16710.5	17062.5	11.6 t

To switch to "self-supporting growth" automatically, several conditions must be satisfied:

1. A sharp increase in the share of investment in production of national income.
2. Intensive development of one or more industries.
3. Political victory of the advocates of modern society over the supporters of traditional society.

In the conditions of Uzbekistan, the above conditions were fulfilled in a certain sense.

At the fourth stage, according to U. Rostow, technical development era will begin, where the level of urbanization will increase and industrial production will be transferred to qualified managers. The beginning of this phase dates back to 1850 in England, 1900 in the USA, 1910 in Germany, 1910 in France, 1920 in Canada, 1930 in Sweden, 1940 in Japan, and 1950 in Russia.

At the fifth stage of high mass-consumption, there is a transition from supply to demand, from production to consumption, i.e. the production is focused only on the consumption matching the demand. Later on, U. Rostow adds the sixth stage of economic growth. This stage, called "the search for quality", is characterized by an increased demand for high quality durable goods [7, p. 230]. In Uzbekistan, the requirements of the fourth and fifth stages must be fully fulfilled to create decent living conditions for the people.

In modern literature, this topic has been studied by many authors. In particular, Collin Constantine revealed the essence of economic structures, institutions and economic performance [17].

The modernization phase of the country's economic development is an important step. Both the developed and the developing countries either have completed this step or are currently in the process of modernization. Modernization is a process of technological upgrade aimed at increasing the competitiveness of products produced (works and services). It is a tool to eliminate technological retardation of enterprises, which has a profound impact on the level of labor, resources and raw materials use. The results of modernization, technical and technological renovation determine the conditions for the rapid development of high-tech, competitive production.

Modernization of the economy is a comprehensive concept, and its essence in economic literature is different. "The modernization is like an elephant: difficult to describe, but easy to recognize when you see one," says a Singaporean political scientist Goh Keng Swee [8, p. 1]. Economic reforms aimed at technological renewal of any production capacities do not always imply modernization. At the same time, any sector of the economy that is subject to modernization does also experience a state of renewal. The theory of modernization reflects the sum of the socio-economic and political development concepts which describe the process of transition from a stable traditional economic system to modernized industrial society [9, p. 12]. The conceptual essence of modernization is evident from the need for fundamental reforms to face the economic, technological, institutional challenges and transition to a new stage in civilization development [10, p. 5].

Secondly, the stage of modernization of the economy will be realized within a certain period of time: as a rule, from 10 to 30 years. Modernization experiences in the developed countries of the world in the second half of the XX century are remarkable. Russian economist Prof. B. A. Heifets and A. B. Chubais have systematized their successful modernization projects [11, p. 23], [12, p. 121].

Table 2. Successful modernization projects in the world

Country Name	Launching of Modernization	Sustainability Development Duration	Period
Japan	Beginning of 1960	The end of 1970	20 year
USA	Beginning of 1960	1980	25 year
Chili	The end of 1960	The end of 1980	20 year
Taiwan	Beginning of 1970	The end of 1990	25 year
Malaysia	1980	Beginning of 2000	20 year
Israel	1980	Beginning of 2000	20 year
India	1980	The end of 2000	20 year
China	1980	Beginning of 2000	20 year
South Korea	1980	Beginning of 2000	20 year
Singapore	1980	Beginning of 1990	10–15 years
Finland	1980	2000	15–20 years
Ireland	1980	2000	15–20 years

Table 2 shows that in developed countries, the duration of the modernization project is definite and between 10 and 25 years. Studying world practice, the beginning of the modernization of economy in Uzbekistan corresponds to the year 2005. The reason for that was the inherited stagflation economy, crisis conditions from the period of ex-Soviet Unions, the structural transformation of 1990s with the period of explosive economic growth. According to the table data, Israel, India, China and South Korea successfully completed the modernization in the early 2000s and achieved sufficient conditions to start using the innovative model of economy.

In the modernization of the economy, one can switch from one model to another. According to many economists and analysts, the models of global economic development vary in different periods or show the power of influence on changes. The structure of global economic development models includes 6 subsystems or submodels [13, p. 4]. These submodels are:

1. Global financial submodel (Global financial system).
2. Sub-model of trade and exchange relations.
3. Global production submodel.
4. Reduction of the population (labor resources) is a global submodel.
5. Institutional regulation of international economic relations submodel.
6. Other self-propagating global submodels.

The countries that use a natural model of economic modernization, developed submodels 1–5 well and have sufficient experience. Changes in submodels 1–5 are the result of the specific features of the countries that have chosen the “catching up” model.

The Decree of the President of the Republic of Uzbekistan PD-5308 as of January 22, 2018 "On State Program on Implementation of the Strategy of Actions for the Development of the Republic of Uzbekistan in 2017–2021 in the Year of Support of Active Entrepreneurship, Innovative Ideas and Technologies" identified certain tasks. Particularly, the third chapter of this program indicates the priorities of economic development and active entrepreneurship support, namely, a step-by-step approach to a new model of economics which consists in: promoting macroeconomic stability, maintaining high economic growth, and developing "smart" technologies, increasing exports of local products, attracting foreign investment, increasing investment and tourist attractiveness of the country. In addition, paragraphs three and four set tasks for the enhancement of structural reforms, modernization and diversification of leading sectors of the national economy, as well as the modernization and accelerated development of agriculture, and assigned the responsible ministries and agencies responsible for their implementation. Also, the timeline for the implementation of the program is clearly defined in months, costs, funding sources and the mechanism for implementing these measures and the expected outcomes.

The document also presents an extensive program aimed at modernization of the construction industry. It develops a strategy for innovation and advanced development of the industry, introduction of innovative technologies. There are measures to encourage the national project for contracting organizations to enter the external markets. The goal is to eliminate bureaucratic obstacles and barriers and provide access to the construction market, revise the existing normative and technical regulations, construction norms and requirements based on world standards. There is a need to form a professional class of qualified builders and architects, thereby eliminating the misconduct based on attracting one-time workers, attracting qualified foreign specialists on a systematic basis and creating conditions for the professional development of local professionals abroad. It is envisaged to consider the interests of building materials manufacturers on the basis of localization projects in the process of public procurement.

At the moment, transition economies are dealing with the transition to innovative development based on the modernization and diversification of the economy [15].

The main principles of the economic policy of transition economies are:

1) economic liberalization;
2) changing the attitude towards property, focusing on the development of the private sector;
3) structural transformation of the economy;
4) inflation control;
5) adaptation of economic entities to new business[5].

The countries with transitional economies attempt to strengthen government stabilization processes, increase competitiveness of national production, and facilitate the implementation of a new market economy [16, p. 227].

In the CIS countries, strategies for the modernization of the economy have been developed since the 1990s and directions of its implementation have been identified. However, not all countries transforming to the new economy had the opportunity to develop and implement the strategy of modernization of the economy evenly. The reason is that the development of technological and macroeconomic parameters has not been uniform, there was no structured program of modernization, and that some countries were lagging far behind the developed countries in terms of scientific and technical development. Nevertheless, the following three areas of economic modernization are characteristic of transforming economies:

- increasing the competitiveness of products;
- prevention of economic risks;
- forming a new management mechanism.

Along with the positive aspects of modernization of the economy, there are specific negative aspects, which are the risks that threaten the economic security of the state and prevent the process of modernization. Modernization of the economy is a necessary stage for the transforming economies. The moderni-

[5] Shcherbanin Yu.A. Mirovaya ekonomika [World economy]. M:.2009. – p. 380.

zation program covers key areas such as technological renewal of production, structural transformation of the economy and innovative development. At the same time these structural elements are characterized by a “catching up” modernization model. In countries with transition economies, we find the answers to some of the questions that are specific to the case study of the “catching up” model of the modernization of the economy and the way in which this model is being utilized. There were conditions in the countries with economies in transition to use the “catching up” model of modernization of the economy. Firstly, in the first half of the XX century, industry had developed, although the production capacities were out of date. Secondly, the high military potential is confirmed by the triumph in the First and Second World Wars. Thirdly, the role of the state in the regulation of the economy is high, which is reflected in the tax, monetary policies and pricing. In the transition period, if the government’s interference in the economy is limited, it might cause negative and severe consequences. The Global Financial and Economic Crisis, which started in 2008, forced some countries with economies in transition, which initially chose the “catching up” model of economic modernization, to change their priorities in order to fight against the crisis and elaborate the measures to overcome its negative consequences. Two of the countries included in the single customs union, Russia and Kazakhstan, have similarities in the modernization strategy. Uzbekistan is one of the transitional economies and the experience of the above-mentioned countries is important in the process of developing a modernization strategy, as it is part of the CIS. According to CIS statistics, in the period 2000–2017 different trends were observed in the study of the main macroeconomic parameters (Table 3).

Table 3. GDP growth rates (in % of the previous year) [21]

Countries	2000	2005	2010	2013	2014	2015	2016	2017
Russia	110.0	106.6	104.5	101.3	100.6	96.3	99.8	101.5
Ukraine	105.9	102.7	104.1	100	93.2	90.1	102.3	102.5
Kazakhstan	109.8	109.7	107.3	106.0	104.4	101.2	101.0	104.0
Uzbekistan	103.8	107.0	108.5	108.0	108.1	108.0	107.8	105.3

Table 3 shows that GDP growth rates declined in Russia, Ukraine, and Kazakhstan in 2000–2016, and went to a recovery phase in 2017, while Uzbekistan achieved a trend of steady growth (over 5%) for 2004. The tendency to decline has been driven by the global financial-economic crisis due to the debt-driven economy of these countries, while the measures taken to overcome the negative consequences of the crisis in Uzbekistan have provided a stable growth.

In the medium term, the goal of modernization of the national economy is to achieve sustainable growth in real sectors of the economy by implementing institutional and structural reforms, increase competitiveness of the national economy, filling internal and external markets with high quality products and modern services, and, ultimately, transform economic system to the trail of innovative development.

Conclusions

Due to these goals, the following tasks of modernization of the economy can be distinguished in the long-term perspective:

- implementation of institutional and structural transformations aimed at effective accomplishment of privatization processes;
- implementation of government programs aimed at ensuring sustainable growth in industry, including machinery, fuel and energy complex, light industry, agricultural processing industry, and implementation of targeted government programs;
- mobilizing domestic resources and capacities to ensure sustainable growth through the use of existing production capacities and alternative energy sources, accelerating localization programs through domestic

raw material resources, expanding regional development among areas, improving efficiency of investment and material-technical resources;

- formation of priority directions of state scientific and technical programs, expansion of the elements of high tech and knowledge economy and innovative development.

Analyzing the structural shifts in the generation of GDP in the national economy from 1991 to 2020, we can conclude the share of services and other sectors had the tendency to increase, while the share of agriculture decreased.

In the long term, the GDP is expected to double by 2030 by means of increasing the share of the manufacturing industry up to 40%. When drafting the industry development strategy of Uzbekistan, the state set the main goal of increasing the competitiveness of production to ensure sustainable growth through delivering high-demand goods for domestic and foreign markets.

Directions for further research

The following points represent the major factors contributing to the sustainable growth of industrial output:

1. An active investment policy aimed at accelerating the introduction of modernization, structural transformations and major hi-tech production capacities.
2. Step-by-step expansion of production localization.
3. Financial support of local producers.

The long-term strategy of modernization of the economy should be based on recent achievements in science, technology and innovation.

To sum it up, the modernization of the economy is closely linked to structural changes. The annual growth of GDP in the leading sectors of the country, including the growth of the manufacturing industry, will vary depending on the sector structure, the volume of investments, the state of the fixed assets, the employment-to-population ratio.

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APPLICATION OF COMPLEMENTARY ASSETS IN MINING INDUSTRY: DEFINITION, NATURE, AND FEATURES

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The article is devoted to the analysis of the possibilities of increasing the efficiency of a mining company by managing specific assets using a complementary approach. The relevance of the work is caused by the fact that the mining industry differs from other sectors of the economy because of the specificity of the mineral raw materials and production processes. The mineral resources assets that form the company's mineral resources potential are unique in nature. Their main feature is the depletion and dependence of the value of mineral raw materials on the influence of a combination of factors, whose action can cause both its decrease and increase. In addition, the specifics of the mining processes determine the organization of activities, complicating the management of a mining enterprise, which, along with constantly changing external factors, forces the management of a mining company to look for new ways to improve production efficiency. The purpose of the study is to establish the role of digital assets in the activities of mining enterprises and determine the necessary requirements for their successful operation. In the course of the study, an analysis of Russian and foreign scientific literature was carried out, the experience of mining enterprises was studied, and methods such as comparative analysis, systematization and generalization of the results were used. The article discusses the growing importance of digitalization for mining enterprises. The problems of introducing digital assets in the mining industry have been identified. The authors substantiated the need for complex integration of digital assets with other assets, and identified the relationships between them. The concept of complementarity in the analysis of intangible assets is disclosed and the characteristics of complementary assets are clarified. It was revealed that it is the complementary assets that contribute to improving the efficiency of mining companies through the development of open innovations, provided that the necessary environment is created. The significance of this study is that it will allow the management of mining companies to make adjustments to the organization of production and management processes in order to increase their economic efficiency. The directions of further research are the presentation of a model for the integration of complementary assets and the development of a methodology for assessing the complex economic effects of the use of complementary assets in mining companies.

Keywords: mining industry, economic efficiency, assets, intangible assets, complementarity

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ПРИМЕНЕНИЕ КОМПЛЕМЕНТАРНЫХ АКТИВОВ В ГОРНОЙ ПРОМЫШЛЕННОСТИ: ПОНЯТИЕ, СУЩНОСТЬ, ОСОБЕННОСТИ

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Статья посвящена анализу возможностей повышения эффективности горной компании за счет управления специфическими активами с применением комплементарного подхода. Актуальность работы обусловлена тем, что горнодобывающая промышленность отличается от других отраслей экономики специфичностью объекта работ и процессов производства. Минерально-сырьевые активы, формирующие минерально-сырьевой потенциал компании, являются уникальными по своей природе. Их основной чертой является исчерпаемость и зависимость ценности минерального сырья от влияния совокупности факторов, действие которых способно вызывать как ее снижение, так и увеличение. Помимо этого, особенности самих процессов горного производства определяют организацию работ, усложняя управление горным предприятием, что наряду с постоянно изменяющимися внешними факторами заставляет менеджмент горной компании искать новые пути повышения эффективности производства. Цель исследования – установление роли цифровых активов в деятельности горных предприятий и определение необходимых требований для их успешной работы. В ходе проведенного исследования был осуществлен анализ российской и зарубежной научной литературы, изучен опыт добывающих предприятий, а также были использованы такие методы, как сравнительный анализ, систематизация и обобщение полученных результатов. В статье рассмотрено растущее значение цифровизации для предприятий горной отрасли. Определены проблемы внедрения цифровых активов в деятельность горной компании. Авторами обоснована необходимость комплексной интеграции цифровых активов с другими активами, определены взаимосвязи между ними. Раскрыто понятие комплементарности при анализе нематериальных активов, уточнены характеристики комплементарных активов. Выявлено, что именно комплементарные активы способствуют повышению эффективности деятельности горных компаний за счет развития открытых инноваций при условии создания необходимой среды. Значение данного исследования состоит в том, что оно позволит менеджменту горных компаний внести коррективы в организацию производственных и управленческих процессов с целью повышения их экономической эффективности. Направлениями дальнейших исследований являются представление модели интеграции комплементарных активов и разработка методики оценки комплексных экономических эффектов от применения комплементарных активов в горных компаниях.

Ключевые слова: горная промышленность, экономическая эффективность, активы, нематериальные активы, комплементарность

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Introduction

A modern mining enterprise constantly faces various challenges, caused by both external and internal factors. Undoubtedly, the mining industry is unique, since it deals with mineral resources, which characteristics are determined by nature. They include the exhaustion and non-renewability, the volume and thickness of the underground mineral, the depth of occurrence, the lack of free access to it, the qualitative composition of raw materials and the presence of impurities, the heterogeneity of the distribution of useful components, the variability of the form of the deposit in the case of solid minerals, and so on. Along with the characteristics of the mineral itself, the characteristics of the host rocks are also determined by natural factors and do not depend on humans, for example, the strength of the enclosing rocks, a tendency to dynamic and gas-dynamic phenomena in the form of rock bursts, rock and gas emissions, water breakthrough into mine workings. This causes not only the possibility of unforeseen situations and accidents in the workplace, but also the impossibility of accurately predicting the costs, which complicates their management and optimization.

In addition to the specific features of mineral resources, the production process and the process of managing production assets also have a number of characteristics that distinguish them from processes in other industries.

Firstly, mining enterprises are characterized by low profitability. This is due to the fact that added value in mining is created mainly during the processing, while the number of consumers of mining enterprises is usually limited, which negatively affects the level of prices and profit. This is driving the need for mining companies to reduce the cost of owning, maintaining and repairing assets.

For example, we have calculated its profitability indicators of the North Urals Mine, the raw materials division of RUSAL company, on the basis of the financial statements posted on the company's website (Table 1).

Table 1. Analysis of the profitability of the North Urals Mine

Indicator	Value, %
Profitability of sales	7,6
Return on assets	3,94
Return on equity	6,77

Source: compiled by the authors based on https://rusal.ru

Profitability characterizes the degree of efficiency of the use of various resources: material, labor, finances, etc. At the same time, there are no standard indicator values of profitability, they vary depending on the industry and the enterprise. For mining companies, the indicators are in the range of 3–7%. This is due to the fact that many enterprises are raw material divisions and are practically devoid of independence in managerial decision making. This leads to limited planning opportunities when implementing investment projects, purchasing equipment, upgrading, etc.

Secondly, the industry is characterized by high capital intensity, which is associated with the need for a large amount of expensive equipment for the extraction of raw materials. As a consequence, one of the characteristics is high capital intensity and, consequently, low capital productivity. Here we can add that the requirement on equipment also determines the high material consumption due to the need for maintenance and repair of this equipment. For example, the construction of new capacities of mining and chemical holdings is estimated at about 1.5 billion US dollars per 1 million tons of P_2O_5 [1].

Third, mine workings as well as specialized buildings and structures have a significant share in the total volume and value of assets. Their specific feature is that, taking into account the proximity of mining production to the place of work and the location of the deposit at a considerable distance from the developed infrastructure, after the closure of the deposit and the liquidation of the enterprise, such fixed assets become illiquid. For example, due to the deterioration of mining and geological and production conditions, as well as the quality of the extracted raw materials at the Kashpir shale deposit, at the end of the last century, it was stated that the further work was inexpedient. As a result, a comparative analysis of the costs of conservation and liquidation of production was carried out, which showed that both options are quite costly. Thus, the conservation of the mine requires the expenditures for electricity, ventilation, pumping water and other processes, which was considered economically unviable. As a result, the mine has been closed, despite the fact that it also implies significant costs for backfilling inclined shafts, equipment removal, reclamation of disturbed land, but in comparison with conservation it is more favorable [2].

Fourthly, the extraction of raw materials is characterized by constant movement in space as the work progresses, which leads to an increase in transportation costs, the need for permanent equipment of the workplace, etc. For example, today, work in underground mines is carried out at a depth of up to 5000 meters, as is the case at the Tau Tona mine in South Africa [3]. This necessitates the solution to the problems of supplying communications, ventilation, equipment delivery using modern methods and new technologies.

For these reasons, managing a mining enterprise, even under favorable external conditions, is a very complex process. And given that the external environment is also very changeable and makes its own adjustments, caused, for example, by changes in prices for raw materials, fluctuations in supply and demand, various political and economic factors, for effective management of mining production, a complex of organizational, technical and economic measures is required, designed not only for a specific enterprise, but also adaptable to constant changes.

The most important factor complicating the management of a mining enterprise is the specifics of the assets of a mining enterprise. The mining company has mineral assets which do not exist in any other industry. Despite the fact that mineral raw materials and mineral reserves are identified as a separate asset by many scientists [4, 5, 6], their characteristics as an asset and the processes of change in their cost are not widely reflected in the literature. At the same time, analyzing the course of the main production process associated with the extraction of mineral raw materials, it is obvious that as the extraction proceeds, the reserves decrease, which, as a result, affects the assessment of the value of the mineral asset. The value of mineral resources is a complex concept and is formed on the basis of a combination of factors that can be combined into several groups [7]: mining and geological, geographical and economic factors.

Mining and geological factors, in addition to reserves of raw materials, also include production conditions (structure, thickness, depth), quality of raw materials (estimated grade of an orebody, ore preparation characteristics), technical and environmental conditions of the deposit. Geographic factors describe the location of a deposit and take into account the availability of infrastructure, for example, transport accessibility. Economic factors include changes in demand in the domestic and foreign markets, fluctuations in raw materials prices, taxation system, and so on.

These groups of factors differ not only in their nature, but also in the degree of stability. According to experts [7], mining and geological and geographical factors are the most controllable, while economic factors are more difficult to predict and manage. A striking example is the changing situation on the rare earth metals market. The mining of rare earth metals began in the 19th century, but a rapid growth in demand was recorded at the end of the 20th century. So, if in 1980 the volume of production of rare earth metals in terms of oxides was 26 thousand tons, then by the mid-2010s it increased to 100–120 thousand tons [8]. This is due to the growing consumption of rare earth metals by the rapidly developing high-tech sector. Naturally, the change in the volume of demand for rare earth metals caused the development of the market and, as a consequence, changes in prices. So, if in the 1980s and 90s China was the leading producer of products, retaining monopoly control over the market thanks to government programs in the country, then from the early 2000s the situation changed, and China began to reduce export volumes. Naturally, given the absence of alternative suppliers at that time, this led to an increase in prices, whose volume was difficult to predict. As a result, if in 2009 the weighted average price of rare earth oxides fluctuated at the level of $10/kg, then in mid-2011 it reached the level of $190/kg [8], which confirms the above-mentioned complexity of forecasting economic factors and their spontaneous nature.

Therefore, it would be a mistake to say that the value of mineral assets definitely decreases with a decrease in their reserves, since the volume of reserves is only one of the factors influencing the evaluation. Considering the total value of the assets of a mining company, we can conclude that a decrease in the volume of mineral reserves makes its negative contribution, but in addition to tangible assets, the mining company also has intangible assets, whose number and variety is rapidly growing in the context of digitalization.

Today, digital assets deserve special attention, as their use affects various industries, including the mining industry. In the academic environment, the volume of publications devoted to the use of digital technologies in the process of extraction and processing of minerals is relatively large. At the same time, both in Russian and in the foreign literature, various kinds of issues are analyzed: from the use of new technical and digital achievements [9–17] to changes in management processes at a mining enterprise [18–20]. The existing publications are distinguished by a variety of approaches. Some authors [9, 10] focus on the kind of extracted raw materials, taking into account their characteristics and problems arising during extraction. Other researchers [11] focus on solving a certain production problem. Still others [12–15], on the contrary, analyze the existing digital technologies and discuss the possibility of their introduction into the industry. The most popular technologies include the Internet of Things [12, 13] and the emergence and development of digital twins [14, 15]. The fourth [16–20] consider the problem comprehensively, from the point of view of the impact of the digitalization process on the industry as a whole, while emphasizing emerging trends and issues, as well as drawing parallels between similar processes in Russia and abroad. At the same time, the authors agree that, despite significant technological progress, the mining industry is not among the leaders in the implementation of digital technologies, also because digitalization is introduced partially. Companies do not always create the necessary infrastructure to operate digital assets, as these assets are viewed separately from their complementary assets.

Despite the fact that the emergence of the definition and concept of complementarity dates back to the nineties of the XX century, these ideas have become relevant in recent years in connection with the development of digital assets. Moreover, if abroad they attract the attention of specialists from different industries [21–22], then in Russia they have not become widespread yet [23–26]. At the same time, today the complementarity of the assets of a mining enterprise remains a topic characterized by a lack of research.

This paper examines the role of new digital assets in the development of a mining enterprise and their impact on the efficiency and value of assets of mining companies.

The object of the research is the Russian industrial enterprises of the mining industry, in particular, the North Urals Mine.

The subject of the research is the economic and managerial relations arising during the formation and functioning of complementary assets at mining enterprises.

Purpose of the study

The purpose of the study is to establish the significance of complementary assets for increasing the economic efficiency of a mining enterprise. To achieve the goal, the following tasks have been set:

- analysis of problems arising in the implementation and use of digital assets;
- determination of the conditions for the most effective functioning of digital assets;
- research into the digitalization of the industry from the point of view of the concept of complementarity;
- determination of the characteristics of complementary assets.

Methodology

We analyzed Russian and foreign literature, including the academic sources and the experience of mining enterprises, devoted to the problems of the industry digitalization, the role of digital assets in the production and management process and the introduction of a complementary approach in management. Current trends are identified, existing methods are systemized, and obtained results are generalized.

Results and discussion

Digitalization today finds application in all areas of the economy, and the mining industry is no exception [19]. The flagship industries in the implementation of digital products and technologies are IT, banking, education, biotechnology and medicine, but the mining industry can also show some success. The heterogeneity is clearly visible in this case, what is expressed in the development of digitalization in the oil and gas industry and in the lagging behind of other sub-sectors. The reasons for this lag are the lack of qualified personnel, the low level of production automation, and the cyber threat defense system that needs to be improved [9, 27]. Existing examples show that while most Russian and foreign oil and gas companies such as Eni S.p.A. (Italy), Equinor (formerly Statoil) (Norway), PJSC Gazprom, PJSC Lukoil are digitizing their fields and developing programs for the development of digital technologies; digitalization has not yet achieved outstanding results at enterprises for the extraction of solid minerals.

At the same time, experts agree that, despite the conservative nature of the industry and the existing problems, digitalization should be considered as a “new paradigm” of development that can significantly improve production performance [9, 10].

Therefore, the company management, who wants to make the production process more innovative, introduces new technologies, not paying enough attention to the current conditions for implementation. Thus, there are examples showing that the acquisition of fixed assets not only will not have a positive effect, but also will lead to problems. For example, Eni S.p.A. had to close the HPC3 hybrid computer project, which was intended for use in the exploration and production of hydrocarbons. The reason, according to the experts, was the incompatibility of the computer with the data obtained from other existing equipment [9], i.e., in fact, digital technologies turned out to be incompatible. Unfortunately, situations of this kind are quite common, despite the fact that the thesis about the insufficiency of the isolated introduction of new technologies has been formed and clearly substantiated in the academic community [20]. In the era of digitalization and the rapid development of technology, a transition to digital thinking is necessary, and it should be carried out at the stage of the company strategy development. Then the management solutions will be integrated into the mining company’s strategy in such a way that they will complement and improve the existing ones and contribute to the growth of their efficiency.

An integrated approach to the digitalization of mining companies should be based on the consideration and assessment of factors in relation to assets. Speaking about the combination and mutual influence of assets, it is necessary to note the theory of complementary assets, introduced by Paul Milgrom [28]. The term “complementarity” reflects the interrelation of changes. Milgrom extended this concept to the resources or assets of the company, which he called complementary, if the effect obtained from the joint use of these assets exceeds the total effect from the use of these assets separately, which can be expressed by the formula:

$$E\ (A1, A2, A3) > E\ (A1) + E\ (A2) + E\ (A3),$$

Source: compiled by the authors

where E (A1), E (A2), E (A3) are the effects of using assets 1, 2 or 3, respectively, E (A1, A2, A3) is the total effect of the joint use of assets.

Separately, we note that it would be wrong to talk exclusively about a positive effect, and there are no linear dependencies between changes in one asset and the efficiency of a mining enterprise. In some situations, a change in one asset leads to a worsening of the situation in the enterprise due to the lack of the necessary complementary asset, which happened in the above stated example with Eni S.p.A.

As for the existing approaches to the consideration of complementary assets, in the most general classification they are divided into three groups: human, structural and computer capital [29].

Human capital is the ability and motivation of employees, their culture, values, relationships.

Structural capital is the organization of activities, its principles and approaches. This also includes decision-making models, the formation and transfer of responsibility, the rules and standards adopted in the company and the business processes. In this case, we are talking about different levels of the organization: from individual work groups and departments to the entire organization as a whole and its interaction with external agents.

Computer capital includes data and systems for their storage, processing and transferring.

Sometimes this classification can be found in a modified form: economic competence, innovative property, computerized information [30]. Moreover, these components can be correlated with the above-mentioned classification, namely:

- economic competencies include human capital, brand, organizational changes;
- innovative property is a narrower category, in contrast to the previous classification, and includes only R&D;
- computerized information contains data and software.

All three components are present in companies, and if the organization itself is stable, then these assets are complementary. However, this statement is true in terms of a static picture. The organization is a dynamic system where all the components interact with each other and change. Therefore, two clarifications deserve special attention.

Firstly, an important asset characteristic is their stability. Assets change under the influence of various factors, but to varying degrees. It is related to their nature and their sensitivity to certain processes. Thus, an asset (or a group of assets) changes faster than others, which, in turn, begin lagging behind. Of course, complementary connections do not allow this gap to become critical, so the system passes into a new stable state, which remains so until the next change. For example, in the mining industry, this can be observed when purchasing new, more modern and high-performance equipment or when implementing hardware and software. The development of computer capital in this way entails the need for employee training, because otherwise this introduction will not make sense. For example, within the framework of the “Technological Breakthrough” program, OJSC MMC Norilsk Nickel has introduced a planning and control system for ore flow, which allows continuous monitoring of the intensity of the ore flow in order to manage the ore blending processes [11]. The functioning of this system implies the presence of a unified geological database and a system for automated accounting of ore movement. At the same time, one of the most important requirements is the creation of a dispatching system for organizing operational management and production control, which is implemented in the company. Thus, the computer capital initiates the development of the structural capital, and taking into account the fact that the efficiency of the system will also be influenced by the motivation of employees and their skills, consequently, the human capital as well. Improving these two components is essential to get all the advantages that were expected by the implementation of a computer asset.

Secondly, it is important to note that assets, in spite of their inequality, cannot be classified in terms of importance. Their mutual influence does not make it possible to single out the main asset, whose value would exceed the value of other assets. The solution to the problem can be possibly found only at the micro level, where the main asset can be determined based on the analysis of the specific enterprise, the industry, the production indicators and goals.

For example, considering a mining enterprise and taking into account the specifics of its work and the requirements for employees, the leading role among the three components of complementary assets should be given to the structural capital. The need for conducting the operations in hazardous conditions makes compliance with rules and standards extremely important. This is also due to the high dependence on natural factors, whose prediction is not always possible even with the use of the most modern technologies. The second place in importance for the enterprise is taken by computer capital, whose development is proceeding at a high rate and, taking into account the non-lagging of other complementary assets, can bring significant benefits. Human capital at a mining enterprise will close this list, despite the development of the concept of corporate social responsibility and its proven need for the society. The mining industry does not belong to the industries where the human capital plays a major role and directly predetermines the efficiency of an enterprise, at the same time underestimating the human capital is also a serious mistake.

So, taking into account the above-described situation, it is impossible to draw a conclusion about its stability. The basis for making managerial decisions on the extraction of raw materials is technical projects, R&D, instructions and regulations. Formerly the structural capital of the company was built on the basis of a minor use of digital technologies due to their weak development. Today, thanks to the growing degree of digitalization of the mining industry, exactly the digital assets provide data on all activities occurring at the field and facilitate their processing and visualization. Thus, over a relatively short period of time, the share of digital asset use has increased significantly, which confirms the high degree of variability of complementary assets. For example, the North Urals Mine today is operating at a depth exceeding 1000 meters, which determines significant risks. In order to optimize production processes, the company uses the PRESS 3D URAL software package, whose task is to identify especially dangerous zones prone to rock bursts [31].

If earlier the mining process was regulated mostly by legislative enactments, today the use of digital assets made it possible to increase the accuracy of predictions and, accordingly, the safety of work.

Speaking about the value that complementary assets have, we want to highlight two important features. Firstly, they represent the sources of innovation needed to create a product or service. Secondly, they facilitate or simplify the course of the innovation process, caused by them or without their participation. For example, complementary assets reduce risk, help lower transaction costs, and so on.

Given that complementary assets contribute to the production and transfer of innovation, providing interaction between the company and the external environment, it can be argued that they represent an important component of open innovation.

The concept of open innovation emerged in the early 2000s with the publication of Henry Chesbrough's book "Open Innovation: The New Imperative for Creating and Profiting from Technology" [32]. The concept quickly became popular and discussed among specialists in the field of innovation management [21, 33, 34]. Its essence lies in the fact that for any company the innovation process is difficult if it takes place in isolation from external market participants. Firstly, not every company is able to develop and implement an innovation on its own. This is determined by the industry the company operates in, its specifics, size, etc. Secondly, by closing themselves off from the outside world, companies often duplicate developments. At the same time, the intellectual potential of employees is spent on already known innovative results, instead of uniting with the potential of stakeholders to solve new problems. In addition, there are cases when companies reject the innovations they have developed due to the impossibility of their use at the moment for a number of reasons. And only spreading the innovations outside of the enterprise allows them to find application [34].

The idea of open innovation determines the need for a company to interact with the external environment in order not only to obtain greater efficiency from the ongoing innovation process, but also to have the possibility to implement the concept. Despite this, in the literature there is a noticeable shortage in the number of publications devoted to the consideration of these topics in a comprehensive manner. Complementary assets and open innovation are considered independently of each other, although openness to innovation does not determine a company's success in itself. At the same time, openness is understood as a combination of factors such as the number of alliances of a company, the variety of partners (universities, laboratories, start-up companies, suppliers, consumers), the share of R&D carried out in external organizations, etc.

For the successful implementation of this idea, a necessary condition is just the development of intangible complementary assets. It is their competent combination and application that will ensure the necessary interaction with the external environment.

Taking into account the analysis carried out, we will single out the main features that assets should have to be classified as complementary ones.

Firstly, two or more assets can be considered complementary when they are linked together in their application. The exact number of assets is determined for each specific situation and enterprise.

Secondly, at least one of the complementary assets must be specific. This determines its use at a particular enterprise, the impossibility of copying and, as a result, receiving benefits.

Thirdly, assets are characterized as real options. This means that the company is able to carry out its activities without the use of such assets, however, their implementation and operation brings a greater economic effect than the refusal to use complementary assets.

Fourthly, one of the assets determines the creation, implementation and use of the other. Moreover, the links between assets are not one-way. The development of one asset stimulates the development of the other, which, undergoing changes, influences the first one.

Fifthly, the constant evolution of assets causes their growth, which, as a result, contributes to an increase in their value for the enterprise and, accordingly, cost. Complementary assets, when used optimally, provide an enterprise with a range of competitive advantages that can improve the efficiency of production processes.

Conclusions

In the course of this study, the following results were obtained:

1. when considering and analyzing the problems arising during the implementation and use of digital assets in the mining industry, it was found that the specific features of the industry do not allow it to be among the leaders in the implementation of digital technologies, however there is already some positive experience, whose development will help companies achieve high results;
2. for the effective functioning of digital assets in the industry, certain conditions must be created, including a developed infrastructure for the implementation of assets and trained personnel;
3. the digitalization of the industry should be considered from the point of view of the concept of complementarity, that is, digital assets should be interconnected with structural and human capital;
4. the assets must have certain characteristics in order to be counted as complementary ones.

A company is not just a complex mechanism, but also a dynamically developing structure; in order to meet the challenges of the environment, it must make a choice in favor of developing its innovative potential. However, the concept of open innovation cannot fully function without the creation of the necessary conditions. The main condition is to support openness with complementary assets. Complementary assets are a combination of mutually influencing intangible assets, they create an environment for the functioning of open innovations and directly affect the growth of their efficiency. The synergistic effect obtained from complementarity allows the company not only to get significant results, but also to state that existing assets, including digital assets that have been actively developing recently, increase their value over time, thereby compensating for the decrease in the cost of mineral assets due to the depletion of the mineral resource base and deterioration in the quality of raw materials.

Directions for further research

The directions of further research are a deeper study of the interrelation of complementary assets at a mining enterprise, the development of a model of their integration, as well as the presentation of a methodology for assessing the complex economic effects of the use of complementary assets in a company.

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ANALYSIS OF INDUSTRIAL DEVELOPMENT IN THE COUNTRY'S REGIONS BASED ON INDUSTRY PROGRAMS 4.0

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Industry is the most important sector of the country's economy of the Russian Federation. Industry has a significant impact on the economic development of the country, for the entire course of its expanded reproduction. Mechanical engineering, metallurgy, chemical production, production and processing of hydrocarbons are most developed in the regions of Russia. Industrialized regions differ in industries and levels of technological development. After conducting research on the indicators and dynamics of industrial production, it is possible to identify the most successful industrially developed regions. The introduction of new technologies requires significant financial resources, and many enterprises have problems with investments. The production of those regions that actively introduce new technologies is effective. It is shown that the industrial revolution led to creation of digital production facilities, automation and robotization of which accelerated production processes and significantly increased quality indicators. Digital transformation is the leading direction of technological development of the industry. The study reveals the role of new technologies, points to the need for their intensive implementation in the industrial sphere, analyzes the state of industry in the regions, reveals the role of digital platforms. It is emphasized that Industry 4.0 requires leading production managers to review their strategic priorities. Digital technologies provide for the creation of communication networks, digital platforms for working with various data, as well as a research base in the country. The participation of the state in the implementation of regional strategies and the formation of high-tech industries is an important mechanism for the implementation of economic policy. The article considers the regions of Russia where the industrial production potential is high and Industry 4.0 technologies are being successfully implemented. It analyzes the extent to which the Russian industry has mastered advanced digital technologies, the scope of application of digital automated lines and modern software products. The role of digital technologies in production management, in the dissemination of knowledge and the promotion of new developments on world markets is revealed. Knowledge, intellectual resources, information technologies, automated systems, the developed infrastructure of the national innovation system, a modern technological platform, and high technologies play an important role in the activation of the innovation process. Effective investment in industry contributes to increasing the competition of manufactured products, updating the technological base. Digital transformation of manufacturing industries is carried out on the basis of the latest equipment, new machines. It is shown that the key factor for the successful functioning of the economy is the high level of development of science, the creation and application of innovative technologies, standardization in the field of high technologies. The main objectives of the established development centers are the activation of innovation activities in the regions, the concentration of resources and factors of production in a limited area.

Keywords: industry, digital technologies, innovation activity, regional development, knowledge bases, intellectual activity results, digital industry standards

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АНАЛИЗ РАЗВИТИЯ ПРОМЫШЛЕННОСТИ В РЕГИОНАХ СТРАНЫ НА ОСНОВЕ ПРОГРАММ ИНДУСТРИИ 4.0

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Промышленный сектор является важнейшим в структуре экономики Российской Федерации. Промышленность оказывает ключевое влияние на экономическое развитие страны, на весь ход ее расширенного воспроизводства. Машиностроение, металлургия, химическое производство, отрасли добычи и переработки углеводородов, транспортные средства наиболее развиты в регионах России. Различные регионы отличаются по отраслям промышленности, уровню технологического развития. Анализируя показатели и динамику промышленного производства можно выделить наиболее успешные промышленно развитые регионы. Внедрение новых технологий требует значительных финансовых средств, проблемы с инвестициями присутствуют у многих предприятий. Эффективны производства тех регионов, которые активно внедряют новые технологии. Показано, что промышленная революция привела к созданию цифровых производств, автоматизация и роботизация которых ускорила производственные процессы и значительно повысила качественные показатели. Цифровая трансформация — это ведущее направление технологического развития промышленности. В исследовании выделена роль новых технологий, необходимость их интенсивного внедрения в промышленный сектор, проведен анализ состояния промышленности в регионах, раскрыта роль цифровых платформ. Выделено, что Индустрия 4.0 требует от руководителей производств пересмотра стратегических приоритетов. Цифровые технологии предусматривают создание в стране сетей связи, цифровых платформ работы с различными данными, а также исследовательской базы. Важным механизмом реализации экономической политики является участие государства в реализации региональных стратегий, формирование высокотехнологичных производств. Рассмотрены регионы России, в которых производственный потенциал промышленности высок, успешно внедряются технологии Индустрии 4.0. Анализируется, в какой мере российская промышленность освоила передовые цифровые технологии, объем применения цифровых автоматизированных линий и современных программных продуктов. Раскрыта роль цифровых технологий в управлении производством, в распространении знаний и продвижении новых разработок на мировые рынки. В активизации инновационного процесса важнейшую роль играют знания, интеллектуальные ресурсы, информационные технологии, автоматизированные системы, развитая инфраструктура национальной инновационной системы, современная технологическая платформа, высокие технологии. Эффективное инвестирование в промышленность способствует повышению конкуренции производимой продукции, обновлению технологической базы. Цифровая трансформация обрабатывающих отраслей промышленности осуществляется на основе новейшего оборудования, новых станков. Показано, ключевым фактором успешного функционирования экономики является высокий уровень развития науки, создание и применение инновационных технологий, стандартизация в области высоких технологий. Основными задачами созданных центров развития выделены активизация инновационной деятельности в регионах, концентрация ресурсов и факторов производства на ограниченной территории.

Ключевые слова: промышленность, цифровые технологии, инновационная деятельность, региональное развитие, базы знаний, результаты интеллектуальной деятельности, стандарты цифровой промышленности

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Introduction

Industry is one of the most important areas of activity and the country’s integration into the world economy. Manufacturing plays a key role. Digitalization in industry is a relevant direction, changing production cycles, allowing companies to fulfill the assigned tasks in a short time and providing them with high flexibility in shaping business models. Implementation of innovative activities at the regional level gives higher indicators related to material resources, high technologies. The rate of progress of innovation processes largely depends on the functioning of regional innovation subsystems, on the readiness of regional enterprises to master new technologies [1].

The purpose of the study is to analyze the industrial development of the country's regions based on the use of Industry 4.0 programs.

The object of research is the industry of the regions; the subject of the research is the level of digitalization processes in the industry of the country's regions.

Methods and technique

The research was based on the works of specialists in the field of digital technologies. Methods, technologies and systems of modern development of enterprises in the context of a new technological order were analyzed. Key systems and components of a digital manufacturing plant were examined.

The level of use of the potential of digital technologies in the region reflects success in all areas of national economic activity. Digitalization is becoming more widespread in the leading industrial regions of the country.

The research information base contains structured information from an interview with representatives of consulting services for digital transformation, as well is with representatives of Russian companies that launched digital transformation programs, experience in the practical use of new technologies.

The goals and main directions of modernization and innovative development of the domestic economy are defined in the Decree of the President of the Russian Federation dated May 7, 2018 No. 204 "On national goals and strategic objectives of the development of the Russian Federation for the period up to 2024".

The economy is in a process of rapid change: new methods of industrial production are constantly being introduced around the world. Scientific research, design work, experimental design, technological developments and experimental production play a leading role in innovation.

Industry 4.0 denotes "new technologies that connect the physical, digital and biological worlds, affecting all disciplines, economies and industries". These technologies have great potential to connect millions of people and high-tech facilities to the network improving business performance. Technological changes are required to meet the current development needs of the industry. The production potential of the region is an important competitive advantage, therefore, for the development of industry and attracting investment, it is important to apply new technologies [2].

The degree of research and scientific development of the topic is a generalized analysis of the known scientific achievements in the selected area. Analytical materials of specialists from Russia, Germany, Sweden, Japan, China, the experience of introducing artificial intelligence, Internet of things, modeling and visualization, cloud technologies, adaptation of automated functions for changes in external conditions are studied.

High potential in the process of using new technologies is transformed into real economic results. In the regions, industry is developing in conditions, when there are enough material, intangible, intellectual, informational, technological, innovative and other resources, as well as human resources to ensure economic activity. The manufacturing sector is subdivided into four main components: mechanical engineering and metalworking, the manufacture of materials for future structures, and chemical products. It is necessary to systematize the key components of the development of modern digital production technologies in various directions in three organizational dimensions: design, production, enterprise management. First of all, a digital platform is developed taking into account the specifics of the machine-building industry and meeting modern trends and requirements formed by market conditions. The leading processes of modern production are as follows: Modeling and optimization; Digital twins; Production system; Digital logistics; Technology transfer; Intellectual property; Project Management. Digital modeling of the work of manufactured equipment in production affects the timing of product development and release. Various methods of modeling, from physical processes and individual assembly units to technological processes and production, in general are widely used in all leading manufacturing enterprises today, providing their industry leadership[1] [3, 4].

Technological development will be accelerated by increasing the innovative activity of organizations, introducing new tools to stimulate their development and supporting the innovation infrastructure. Moscow, St. Petersburg and the Nizhny Novgorod region became the leaders in the ranking in science and technology. The leading positions of the two capitals are due to the historically high level of development of science and technology, the presence of leading research institutes of fundamental and applied orientation, high-tech industries.

The economy of the Leningrad Region is developing thanks to of various industries: the most significant segments are mechanical engineering, electric power, aluminum and forestry. There is an active introduction of new technologies in these regions. They are related to the digitalization of design and technological activities, the introduction of various operational planning and dispatching systems, and the modernization of equipment. Many operations are performed by machine tools, robots and computer-aided design systems. The level of automation at the enterprises of the Republic of Tatarstan, Khanty-Mansi Autonomous Okrug – Yugra, Tyumen Region, Yamalo-Nenets Autonomous district is also high. Active work is underway to create Factories of the Future with high-tech enterprises. For example, shipbuilding (Sredne-Nevsky shipbuilding plant Malakhit), aircraft and helicopter engineering (United Aircraft Corporation / Sukhoi Civil Aircraft / Irkut Corporation / Ilyushin Aviation Complex). The software and hardware systems used at these enterprises work in parallel to perform one or more homogeneous tasks. It is possible to increase the efficiency and profitability of production with the help of the introduction of such complexes, and to reduce the volume of working capital.

Blockchain-based solutions (8.1% of respondents), big data (6.9%), artificial intelligence (6.1%) are used among the planned digital technologies for development [5].

In recent months, at the initiative of the President of the Republic of Tatarstan, machine-building enterprises of the Republic of Tatarstan have joined the digital transformation processes: NPO OKB named after M.P. Simonov, Kazan Engine-Building Production Association, Kazan Helicopter Plant and KamAZ. The industry is characterized by high-tech industries. Kaluga Region is implementing a pilot project to create a national data management system. Technical support is provided: the software collects, analyzes, organizes, visualizes the data received from the sensors, and helps a person make decisions or makes them automatically. But the digitalization of production is also constrained by the insufficient penetration of industrial automation systems (MES systems, digital lines). The machine-building complex is one of the significant sectors of the economy, the level of development of which largely determines the state of the economic potential of the Russian Federation, its competitiveness in the domestic and world markets, as well as the state's defense capability [6].

Trends in the development of mechanical engineering until 2030 will be associated with the implementation of measures for the technological re-equipment of enterprises, increasing design work aimed at creating new competitive types of products. The development of the digital economy requires a strong talent pool. For technological leadership, enterprises need to carry out intensive research preceding technological development, create the results of intellectual activity and carry out technology transfer. In addition, organizationally, the following points are of great importance:

- creation of platforms for interaction and knowledge exchange;
- integration of science and technology;
- coordination of efforts between all participants;
- development of a communications network;

[1] "Digit" goes up: production automation dynamics in Russia/RBK partnership project. Digital economy («Цифра» растет: как развивается автоматизация производств в России/партнерские проекты РБК. Цифровая экономика), https://plus.rbc.ru/news/5b5e4f937a8aa9225f10e22a

- dissemination of best practices;
- priorities for the development of the cluster;
- support for new projects in the field of communications;
- advisory, methodological and organizational assistance [7, 8].

The first digital industry standards in the country were developed by the Cyber-Physical Systems Technical Committee based on RVC with the support of the Ministry of Industry and Trade of the Russian Federation. The standards are aimed at the effective implementation of digital technologies in the Russian industry, the development of high-quality and independent solutions, as well as ensuring their compatibility. The new standards form the basis for the creation of two new series of national standards for Industry 4.0. They focus on virtual production systems and the convergence of digital technologies and IT systems in industrial enterprises. For example, the preliminary national standard (PNST) "Industrial automation systems and their integration". This standard specifies provisions for ensuring the safety of industrial plants using automatic process control devices.

Next "Assessment of convergence of informatization and industrialization for industrial enterprises. Part 1. Structure and Typical Model" defines the basic principles of the process of integrating information technologies into industrial production.

The digital transformation model includes the following directions:

1. Creation of a regulatory environment for digital transformation of the industry.
2. Creation, integration and development of platforms of the state information system of industry (GISP) for the implementation of industrial policy.
3. Digital transformation of manufacturing industries [9, 10].

The introduction of new technologies can change the order of using resources by personnel and administration and thereby affect the competitive advantages of companies. The main technologies of Industry 4.0 have been introduced: big data, cloud computing, mobile technologies and social networks. To ensure the dynamic development of the national industry, appropriate macroeconomic conditions and regulators are needed, which must include an effective mechanism of state scientific, technical and industrial policy [11].

Principles of building science and technology policy in the regions:

1. Recognition of intellectual property and products, technologies, services created on its basis, which determine the level of development and competitiveness of the Organization.
2. Use of the results of patent research to determine the priority areas of scientific and technological development. The organization and the concentration of resources in these areas.
3. Ensuring the necessary and sufficient legal protection of the rights to results of intellectual activity embodied in the products of the enterprises in the relevant territories.
4. Considering the rights to results of intellectual activity as intangible assets in order to increase the capitalization of the organization.

The increasing role of knowledge and intellectual capital leads to a change in the organization of the innovation process both within individual enterprises and in individual regions within global value chains. Enterprises form business models to test sustainability and flexibility to changing operating conditions when the external environment requires new management strategies [12, 13].

Discussion

A number of technological areas provided in the federal program "Digital Economy of Russia", are already being tested in practice in Moscow. The Digital Russia Index reflects the presence and success of initiatives related to digitalization at the regional level. Each event is categorized into one of seven key sub-indices:

- regulatory and administrative indicators;
- personnel and training programs;

- research competencies and technological groundwork;
- information infrastructure;
- Information Security;
- economic indicators;
- social effects.

Internal backbone factors in relation to the regional industrial complex are:

1) competitive ties characterizing the level of competition within the industrial complex, as well as between enterprises and organizations;

2) cooperative or interaction links, which can be divided into:

- production ties characterizing the degree of interaction of enterprises with each other within the industry, as well as with service and support organizations;
- innovative ties characterizing the degree of innovative activity of enterprises and organizations, the level of their interaction with educational and research institutions and among themselves in terms of the introduction and dissemination of innovations.

Industry 4.0 leads to massive adoption of cyber-physical systems in production, automation of most production processes, installment of artificial intelligence to devices, and introduction of many other modern technologies. All this has a significant effect on increasing productivity and reducing production costs. The Industry 4.0 program includes the following areas:

- digital modeling as one of the basic directions of the implementation of the Industry 4.0 program, which will be actively used in production processes, including virtual modeling of the surrounding physical world to obtain actual data;
- industrial Internet of Things (sensors and equipment in production are united into one network by a hierarchical structure and are subject to a single production management system);
- augmented reality (applicable for various purposes, including when choosing parts of various structures in a warehouse, displaying instructions for the repair and maintenance of equipment);
- big data (BIG DATA) and business analytics used for optimization of product quality, energy saving and improvement of equipment availability). The need to process large databases requires further improvement of “cloud services” [14, 15].

One of the first Russian companies that introduced the programs of Industry 4.0 was SIBUR (Regional Center in Tomsk). The level of technological equipment of the enterprises is one of the highest in Russia. SIBUR uses advanced solutions, such as an improved technological process management system (APC), production system (MES), LIMS laboratory system, SAP ERP enterprise management system, and business processes management system (BPMS).

In SIBUR, Big Data tools are used to maximize the performance of installations and improve product quality, mobile applications, virtual and augmented reality, video analytics, robots, drones and other digital products. Datascience tools are used: online consultants and predictive analytics.

In Nizhny Novgorod, digital production in OJSC TEPLOTEHNIKA is one of the recognized leaders in the production of high-tech products for the aviation industry, which has its own experimental design bureau, research, testing and production base. The TEPLOTEHNIKA company has created a functional model from the BigData zone using machine learning algorithms, systems for construction and storage models. In Tyumen, a modern intelligent control system has been created for an oil-refining factory. This platform created a practically holistic human machine interface to manage a new plant installation, which allowed the operators to receive information on the production process and make the necessary solutions to eliminate the arising problems.

The benefits of digital transformation are best seen in examples. For instance, OJSC KAMAZ created a special Digital Transformation Center, which has already made it possible to implement several successful projects at once. The digitalization of industry is the concept of a new digital space, a unified system integrating production machines, life support and safety systems of the enterprise, that is, all the electronics of the organization. Sensors and detectors make it possible to combine various physical objects into a virtual network, in which they can interact with each other without human involvement. The main benefit of digitalization lies in the improvement of enterprise productivity by reducing time.

To manage innovation activities, improve the efficiency of innovation processes, the Ministry of Industry and Trade of Russia monitors regional and sectoral projects for the digital transformation of industrial enterprises. There are digital platforms created that have a significant impact on the development of industrial enterprises.

Artificial intelligence is the main direction in the development of control systems, which can help to get the most out of existing industries and build new, most efficient systems. The development of artificial intelligence (AI) systems has made it possible to create automation systems of a fundamentally new level [16, 17].

Results

1. Digital technologies allow you to analyze the situation in real time and maintain performance when changing control objectives, unforeseen changes in the properties of a controlled object or environmental parameters. At the design level – to improve the efficiency of new product development, automate the selection and evaluation of suppliers, when analyzing the requirements for spare and component parts. At the production level – to improve business processes and coordinate various production systems. At the logistics level – to improve the planning of transportation routes, reduce the delivery time of raw materials and ensure their predictability, as well as track shipments and the delivery process at all stages.

2. The system is capable of changing the control algorithm and looking for optimal and effective solutions. Artificial intelligence will carry out production, quality control, reduce design time and reduce waste, improve product reuse.

The use of intelligent assistants helps to reduce the number of personnel errors, simplify the production process and reduce downtime when rebuilding technological processes. It can also choose a market segment for promoting products on the foreign market, increase export volumes, and carry out production development forecasts based on objective statistical data.

3. Cyber-physical systems can improve production processes by providing real-time data exchange between such elements as industrial equipment, logistics, business and customer management systems. In addition, cyber-physical systems allow automatic monitoring and control of the entire process, including the adaptation of production to the current needs of the customers [18, 19].

Conclusion

The industry of the regions introducing new technological developments becomes competitive. The country's economy based on the development of the regions shows stable results. Digital platforms have a significant impact on the development of industrial enterprises.

The Industry 4.0 project and program provides for the digitalization and integration of technological, production and business processes vertically throughout the enterprise, from product development and procurement to production, logistics and in-service maintenance. The use of software products in the production cycle of industrial enterprises shows sustainable development of the industrial sector and the economy of the regions.

The presence of digital competencies is important for the successful implementation of the Industry 4.0 concept in industrial enterprises in the regions of the country. Quality analytics of data is a mandatory requirement for the successful implementation of digital platforms in enterprises. It is necessary to implement the tasks of the joint transition to digital production management with the broad integration of business partners within the framework of the value chain and the transition to open platforms (Open Platform for Smart Manufacturing).

Clustering is the real possibility of successful introduction of the cross-cutting technology.

It is important to use international positive experience for applying a flexible production concept (Agile Manufacturing) based on cross-functional production teams. The teams can move between cluster organizations as needed, depending on the production system. In the nuclear industry, Rosatom is already actively using certain elements of digital production in the creation and design of stations and equipment.

Also, advanced companies, like KAMAZ, Joint Aviation Corporation, Russia helicopters produce serial high-tech products and compete in the global market. STVERSTAL actively uses mobile devices to provide transparency for maintenance and repair of equipment, as well as automate personnel planning processes.

Digital transformation is actively used in such areas as advanced analytics, the use of big data for decision-making.

TechNet roadmap proposed by the government in the frame of Industry 4.0 ensures active introduction of new technologies: digital design and modeling; new materials; 3D printing; CNC technology; "smart" sensors; industrial robots; enterprise management information systems; Big data and industrial Internet and others.

The Network Plant concept proposed by Udmurt Machine-Building Cluster suggests that the participants of the production network (cluster), having automated planning and control of production facilities, receive the external information about the production capacity loading reserves. The concept is based on the use of a digital technological platform – a set of software and hardware tools to ensure cloud technology, open data, appropriate applications and services. All information about the "network factory" is stored on cloud servers and integrated with the information systems of the participants of the "Network Plant".

Large enterprises are just beginning to introduce separate elements of Industry 4.0. The domestic industry is gradually approaching the use of the best practices of foreign industrial production, network interaction, organization of scientific and educational activities and the need for adaptation to a particular industry.

Directions for further research: analysis of the practical results of the introduction of digital technologies in the industrialized regions of the country and connecting elements, indicators of economic development.

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SCENARIO APPROACH TO BUILDING PREDICTIVE MODELS FOR THE DEVELOPMENT OF REGIONAL HEALTH SYSTEMS

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The article is devoted to the problems of scenario modeling in relation to solving a number of problems of managing the health care system of the Perm Territory, which in recent years has attracted attention of the development of a number of promising projects to develop this industry, to expand the availability of medical services and to improve the level of medical care for the population. Any good-quality project must be directly linked not only to the future periods of its implementation, but also be scientifically justified in terms of insuring all kinds of risks and threats that will stand in the way of the successful completion of the project. Therefore, recently all kinds of projects, programs and plans are often developed using the so-called scenario approach. Several options for the development of events with this approach are offered to the appropriate circle of leaders or the power structure for the subsequent adoption of an appropriate management decision. The authors of the article consider the main provisions and principles of the scenario approach using the example of the development of the health care system of a particular subject of the federation, which makes the material proposed for consideration very relevant. The authors also define, as they see it, the main result of improving the industry in the form of a target and a national goal: the expected (future) life expectancy of the population of the study area. This socio-economic indicator, which has all the signs of fatefulness, is considered by the authors to be a priority analytical indicator of the level and quality of an effective life of a Russian. The latter determines the purpose of this study. The authors consider the construction of dynamic multivariate models of industry development options for a period of up to three years to be an efficient tool for analyzing and forecasting this indicator, which is presented in the article in the form of five simultaneous equations of multiple regressions. The results of this construction are continued by discussion, and the article ends with a list of conclusions.

Keywords: management decision, forecast, plan, scenario, risk, threat, probability, national economy, health care system, forthcoming (expected) life expectancy, econometric model, statistical estimation, random component

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СЦЕНАРНЫЙ ПОДХОД К ПОСТРОЕНИЮ ПРОГНОЗНЫХ МОДЕЛЕЙ РАЗВИТИЯ РЕГИОНАЛЬНЫХ СИСТЕМ ЗДРАВООХРАНЕНИЯ

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Статья посвящена проблемам сценарного моделирования применительно к решениям ряд-да задач управления системой здравоохранения Пермского края, который в последние годы обратил на себя внимание разработкой ряда перспективных проектов по развитию данной отрасли, по расширению доступности медицинских услуг и по повышению уровня медицинского обслуживания населения. Поскольку любой добротный проект должен иметь непосредственную привязку не только к будущим периодам своей реализации, но и быть научно обоснованным с точки зрения страхования всевозможных рисков и угроз, которые встанут на пути успешного завершения проекта, в последнее время всяческие проекты, программы и планы часто разрабатываются с использованием так называемого сценарного подхода. Несколько вариантов развития событий при таком подходе предлагаются соответствующему кругу руководителей или властной структуре для последующего принятия надлежащего управленческого решения. Авторы статьи рассматривают основные положения и принципы применения сценарного подхода на примере развития системы здравоохранения конкретного субъекта федерации, что делает предлагаемый к рассмотрению материал весьма актуальным. Авторы же и определяют, как им представляется, главный результат совершенствования отрасли в виде целевого показателя и национальной цели – ожидаемой (предстоящей) продолжительности жизни населения исследуемой территории. Этот социально-экономический показатель, обладающий всеми признакам судьбоносности, авторы считают приоритетным аналитическим индикатором уровня и качества эффективной жизни россиянина. Последнее определяет цель настоящего исследования. Работоспособным инструментом анализа и прогноза этого индикатора авторы считают построение динамических многофакторных моделей вариантов развития отрасли на период до трёх лет, что в статье и приводится в форме пяти одновременных уравнений множественных регрессий. Результаты подобного построения продолжены обсуждением, а статья завершается выводами. Ключевые слова: управленческое решение, прогноз, план, сценарий, риск, угроза, вероятность, национальная экономика, система здравоохранения, предстоящая (ожидаемая) продолжительность жизни, эконометрическая модель, статистическое оценивание, случайная составляющая.

Ключевые слова: управленческое решение, прогноз, план, сценарий, риск, угроза, вероятность, национальная экономика, система здравоохранения, предстоящая (ожидаемая) продолжительность жизни, эконометрическая модель, статистическое оценивание, случайная составляющая

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Introduction

The mechanism for managing the national health care system, which developed during the period of a transitional market economy and has characteristic recognizable features of the organizational and economic order, suffers from noticeable systemic deficiencies and contains significant internal contradictions. Most of the contradictions and shortcomings noticed in the vast scientific literature were recorded and analyzed in detail, while the scientific community and society found a more or less stable agreement on the ways to overcome them.

The managerial decisions made by the power structures of different levels in recent years as part of the modernization of the industry meet with a serious misunderstanding of the general population, and they generate heated discussions among specialists. And all this provided that all stakeholders in the modernization process want a radical improvement in the health of the Russian population and are looking, both separately and together, for formulations of specific upcoming managerial decisions and ways to regulate the industry in order to truly improve it.

In the regulation of health care, the state determines the goal, objectives, directions, principles of state policy, sets the amount of budget financing and tries to create a system of efficient regulators. The objects of the health care system, which are regulated by the state in one way or another, include all institutions and subordinate health services. The main body for achieving goals and solving problems in the health sector is the Ministry of Health of the Russian Federation (MoH).

This authority is also entrusted with the task of forming state policy and monitoring its implementation, especially since the allocated financial content of the industry and contribution to GDP are very significant. Thus, the share of Russian healthcare in the expenditure side of the budget for 2020 (in the author's assessment of the structure of the budget list) was slightly more than 4.0%. The government of the country and the Ministry of Health of the Russian Federation are also developing tools for the effective functioning of the industry, determine state standards, carry out forecasting and planning, and form a state order program in order to provide the healthcare sector with adequate resources and reserves. However, any of the most perfect goal-setting needs mechanisms for achieving goals, in which scientifically based schemes for making appropriate management decisions play an important role.

In special areas of economic analysis and applied mathematics, problems, technology and techniques for adapting decision-making theory, which developed rapidly abroad in 1950–1960, to a variety of practical problems that have a certain national economic and targeted socio-economic significance, were studied. After an initial rapid influx of theoretical work in the field of corporate time planning, by the end of the 1980s there was a certain lull. Only in the productive 90s, interest in this topic has renewed in connection with the emergence of new cybernetic algorithms and with the dramatically increased processing power and increased volumes of relevant information. This, in turn, led to the emergence of real opportunities to create original science-intensive and practical applications with a truly innovative character [1, 6].

Review of literary sources

Since the 60s of the last century, the theory of managerial decision-making has been widely adopted by modern mathematical and statistical methods. Therefore, in 1965, the American scientist L.A. Zadeh (*Lotfi Alasker Zadeh*) published his work [20], which laid the foundation for the theory of fuzzy (uncertain) sets and developed an independent version of the terminological apparatus on fuzzy (continual) logic. The emergence of algorithms and operations based on fuzzy sets found their application in machine electronic systems of logical inference of expert systems by the end of the 70s and the beginning of the 80s. And later, when predicting the election results, when assessing atmospheric pollution and the state of the environment, when constructing histograms of the ratios of the factors taken into account in the triad of consumer effective demand, price / quality / time, such algorithms and operations proved their suitability for making managerial decisions [5].

In the 80–90s, mass microchips based on the principles of fuzzy logic began to appear on the market, which are especially suitable and useful in creating all kinds of robots, and then in the development of long-awaited artificial intelligence systems. The zero years of the 21st century have been directly related to the creation of more or less plausible scenarios for the development of diverse economic schemes. Moreover, the mechanisms of such scenarios were also based on the ideology of fuzzy logic and fuzzy sets, while the scenarios were primarily developed for large corporate-type businesses, military-industrial complexes and military affairs itself.

At the same time, in the 70s, varieties of the method of expert estimates were created. It was at that time, thanks to E.A. Feibenbaum (*Feibenbaum Edward Albert*, 1971), a professor of Stanford University, an interpreter for mass spectrograms appeared under the working name DENDRAL, which served as a prototype for all expert systems. Already in 1976, the MYCYN expert product (a subsidiary version of DENDRAL) was registered for the practical diagnosis of blood for bacterial and viral infections, which was a full-fledged expert system with unique analytical capabilities of the pattern recognition procedure in the screening and testing mode [16]. In the 1980s and especially in the 1990s, as well as the zero years of the 21st century, later innovative expert systems and advanced methodology of expert assessments have found their widest application in sectors of the economy. They were, above all, for the prompt adoption of scientifically grounded management decisions.

At the end of the 20th and the beginning of the 21st century, similar and related studies were continued, in particular, in the works of essentially his own views, of neo-globalist F. Fukuyama (*Francis Fukuyama*) [9]. The results achieved in this narrower area were used to simplify procedures for solving real applied problems by taking relatively rational and conditionally ranked measures in those areas of social life that are traditionally considered vital, truly problematic and complex. Such areas then and now include state and municipal government, including local government, military and foreign policy, medical diagnostics and health systems [6].

The rates, which usually correspond to the level of the identified *threat metrics* and the state of the organism of sick national economies, are extremely high when making wrong[1] or erroneous[2] managerial decisions here, as nowhere else. The nature of such a peculiar socio-economic threat measurement is determined not only by industry and commercial risks, but also by country, political, demographic and other types of risks. This circumstance (quite pluralistic views on the nature of risk and threat) forces us to apply a systemic and integrated approach to probabilistic assessment of risks and threats to the implementation of socio-economic programs and projects of different levels [17].

The systemic and integrated approaches are traditionally provided using both frequently used measurement methods, for example, expert assessments, categories of elasticity and sensitivity (measured sensibility), decision trees, randomized Monte Carlo algorithms (simulation modeling) for optimization problems, and purely theoretical novelties of the type: scenario analysis algorithm, hidden Markov models[3], R.E. Kalman, neural networks and dynamic Bayesian networks for temporal models. The latter are based on the fruitful and in no way outdated ideas of network processes by the British mathematician T. Bayes [11].

This is a rather conventional novelty of the productive 60s of the 20th century in the form of scenario algorithms, gradually formed from the individual achievements of mathematical statisticians and was based initially on the technology of predicting political and social processes of Ch. G. Kahn (Charles H. Kahn) [16] and in the study [15]. The theoretical innovation turned into a conceptual essence when assessing strategic management decisions in the works of Hawken P., Ogilvy J., Schwartz P. [14] in the 80s. Then it was further elaborated in the 90s, when developing alternative options for the formation scenarios for the future development of commercial structures and large joint projects of business and government in the work of P. Schoemaker [18], as well as in the works of famous Russian scientists [23, 24, 25].

As a result, in less than 20 years of the 21st century, scenario analysis has developed as an independent and rather fastidious approach to making management decisions on a probabilistic basis. It is the probabilities that order the stochastic depths of the unknown that have recently provided themselves, in the opinion of the authors of the article, a certain way of total accounting for the countable measure of uncertainty / uncertainty or the degree of entropy / disorder of systems that arise either for reasons of forced savings of various kinds of efforts, or the actual absence of special knowledge (sometimes both at the same time). The attempts of some economists to apply the conceptual apparatus of the concept of entropy to political processes and to formulate a certain concept of political entropy, the authors of this article consider as having no prospects[4].

Purpose and formulation of the problems of the study

As the experience of domestic administration shows, skillful public administration of such a difficult object as the national health care system even in the difficult post-crisis conditions of the Russian economy, building sound strategies for the development of the industry under study with appropriate combined

[1] The authors see here a type I error with falling into the situation of rejection of a true null hypothesis H_0. The countable probabilities of getting a type I error are calculated using Bayes' Theorem. Figure 3 explains the place of the type I error.

[2] In this case, we understand a type II error, when the initially incorrect / incorrect statistical zero-hypothesis H_1 is mistakenly confirmed / accepted – an alternative hypothesis. For more detail, see [24].

[3] For example, the well-known so-called hidden Markov model, which is a temporal probabilistic model, where the state of the process is described using a single discrete random variable, and possible values of this variable can be possible states of the environment, territory, etc. algorithms.

[4] Yavlinsky G.A. "Apple" wars // "Novaya Gazeta" No. 14 dated 02/10/2021. S. 10–11.

financing allowed a separate subject of the federation, which occupied the 83rd place in the Russian Federation, to sharply rush up to the 3rd place[5]. Here we specifically talked about the successful reform of healthcare in the Kirov region. On 10/22/2020, the Governor of the Perm Territory (PC) D.N. Makhonin in his speech at a meeting of the local legislature announced an equally decisive and rather ambitious approach[6].

The current governor of the PC outlined his strategy as follows: "The primary task is to modernize healthcare. One of the main priorities is personnel. Today, based on the experience of combating coronavirus, we can say that the main difficulty in providing medical care is a certain staff shortage. Compared to the average Russian medical supply, the PC looks not bad, but there are enough problems. Therefore, we include an increase in funding for the "Zemsky Doctor" program (twice) in the budget; we will continue to implement the "Zemsky Feldsher" program. We will strengthen cooperation with the Perm Medical Academy so that as many graduates as possible stay to work in our medical institutions. We will create better working conditions and modernize infrastructure."[7]

The governor outlined a number of priority tasks for the analyzed industry to the regional authorities, namely, increasing the availability of medical care, regardless of place of residence, using the so-called "mobile clinics", digitalization of units, settlement of the personnel problem of medical personnel, repair and construction of medical facilities, renewal of medical equipment and an ambulance fleet, the creation of medical aviation, the fight against oncology and cardiovascular diseases. Already in 2020, as part of the development of the sanitary aviation system, a helipad appeared in a small town Chernushka.

To solve these tasks for the development of health care for the period of 2021–2023, 180 billion rubles are allocated (see Table 1), and in terms of the development of its own medical infrastructure, the PC, as foreseen, will reach a kind of interregional records. Thus, by the end of the three-year period, it is planned to commission 24 new medical facilities in different territories of the region, for which about 8 billion rubles of budgetary funds are allocated. In particular, already in 2021, it is planned to build new medical buildings in Cherdyn and Yurla, four polyclinics in the capital of the region, including those three for children that were not put into operation according to the 2019 Program[8]. Buildings are being renovated in the region feldsher-obstetric points (FOP) and rural medical outpatient clinics (RMOC) are being equipped, new and state-of-art medical equipment is being purchased. For example, in 2020, the PC authorities procured about 3.5 thousand units high-precision equipment, including MRI, CT and ultrasound machines.

The head of the region considers the digitalization of the industry an important point in the strategy for the development of medicine (so far, however, not reflected in the program itself), which will make almost all buildings of polyclinics and hospitals available on the Internet. During 2021, it is planned to connect most of the FOPs to the network, which will open up the potential of telemedicine and, accordingly, will affect the quality of services for those in need, regardless of where they live. Currently, the overwhelming number of residents of the region have an electronic medical record, and all healthcare institutions are already connected to the Unified Information System (UIS), which gives bright hopes for the implementation of the governor's ideas on digitalization of the industry in the PC.

Commenting on the content of the speech of the governor of the PC, one can understand that a specific regional health care system requires a fundamental update based on radical modernization, and not a multi-step optimization of the desired system in the mode of a long-term and painful procedure, but sluggish reform. The governor presents modernization in the form of consistency and compliance of the provision of medical care to the population with modern conditions for the development of medical science, the achievements of practical health care and the requirements of advanced bases of socio-economic standards, including the level and quality of life of Russians [6].

[5] Gaidar M.E. Debriefing / URL: https://echo.msk.ru/sounds/stream.html. (date of access: 12/14/2020).

[6] Speech by the Governor of the Perm Territory // Transformations in the PC health care system. URL: https://www. permkrai.ru/news/dmitriy-makhonin-zayavil-o-preobrazovaniyakh-v-sisteme-zdravookhraneniya-permskogo-kraya. (date of access: 11.12.2020).

[7] Transformations in the PC healthcare system. URL: https://www.permkrai.ru/news/dmitriy-makhonin-zayavil-o-preobrazovaniyakh-v-sisteme-zdravookhraneniya-permskogo-kraya. (date of access: 11/12/2020).

[8] Decree of the Government of the PC of June 17, 2019 No. 411-p "On approval of the Program" Development of children's healthcare in PC, including the creation of a modern infrastructure for helping children." (date of access: 12.12.2020).

Table 1. The main parameters of the budget of the Perm Territory in 2020 and the plane for 2021–2023

No. p/p	Name indicator	2020	2021	2022	2023
1	2	3	4	5	6
1	SME turnover at comparable prices[9], RUB bln	837.0*	869.0**	902.0**	936.0**
2	Fixed capital investments, RUB bln – to the same period, %	229.0 97.0	252.0 97.0	275.0 105.0	294.0 98.0
3	Export, $ billion	3.0*	5.0***	5.8***	5.4***
4	PC budget revenues, RUB bln Chain growth rate, %	141.8* –0.32	145.6** +2.61	156.6** +7.55	165.5** +5.68
5	Budget expenditures, RUB bln Chain growth rate, %	111.7* +0.21	127.4** +14.06	136.5** +7.14	144.8** +6.08
6	Development budget expenditures, RUB bln – in% of line 5	31.4* 28.07	35.7*** 28.02	38.9*** 28.50	41.3*** 28.52
7	Regional budget deficit, RUB bln – in % of income (of the amount of line 4) – in % of expenses (of the amount of line 5)	17.9* 12.61 16.03	18.2* 12.50 14.29	20.1* 12.84 14.73	20.8* 12.57 14.36
8	Budget expenditures on healthcare in PC, RUB bln Chain growth rate, %	55.0** +3.93	57.5** +4.55	60.0** +4.35	62.5** +4.17

Note: * estimate; ** plan; *** forecast.

Source of information: Sat. Macroeconomic statistics of the PC.

Such modernization congruence includes training of medical personnel, optimization of networks of medical institutions, real availability of medical care for any resident of the region, clear programmatic steps in the development and subsequent implementation of the Strategy for the development of the PC health care system. Certain information on filling resources for the implementation of the three-year plan is presented in Table 1.

According to analysts, PC budget losses in 2020 will amount to about 29 billion rubles, with projected federal budget subsidies of 7.7 billion rubles. At the same time, the budget deficit in 2020 is 38 billion rubles, almost 97% of it will be covered by bank loans (by 37 billion rubles with the regional government debt of 4.06 billion rubles).

And if a full-fledged strategy, program and plan for the development of the PC health care system under the leadership of the last governor has yet to be developed (in contrast, say, from the "Strategy for the development of small and medium-sized businesses until 2030", which was developed by the regional Agency for the Development of Small and medium-sized businesses (SMEs) and which was presented on December 11, 2020 at a meeting of the government of the Kama region[10]), then more detailed judgments should be made about the technologies of professional strategizing [25] in the healthcare sector in this article. In particular, deal with the representation of classical planning problems, i.e. with methods of algorithmization of object states, actions and goals of the control system, as well as clarify the problems of scenario modeling, which serves as an advanced toolkit of strategy technology, strategic management methodology and methods of prospective analysis.

Taking into account the above, the authors of this article consider the main provisions and principles of the scenario approach using the example of the development of the PC healthcare system, which makes the material proposed for consideration quite *relevant*. The authors see the main result of improving the industry in assessing the target and national goal – the expected (upcoming) life expectancy of the popu-

[9] In the implementation of plans for the development of the regional healthcare system business entities play an active role in the PPP (public-private partnership) regime.

[10] URL: https: //xn-90aifddrld7a.xn--p1ai/novosti/news/permskiy-kray-stal-pervym-regionom-razrabotavshim-strategiyu-razvitiya-malogo-i-srednego-biznesana. (date of access: 20.12.2020).

lation of the study area. This socio-economic indicator, which has all the signs of fatefulness, is considered by the authors to be a priority analytical indicator of the level and quality of an effective life of a Russian. The latter determines *the purpose* of this study.

The authors consider the construction of dynamic multifactor models of industry development options for a period of up to three years to be an efficient tool for analyzing and forecasting this indicator, which in the article defines a number of special *tasks*: the implementation of the stages of the scenario approach and the construction of a predictive model in the form of a system of five simultaneous equations of multiple regressions.

Research Methods, Methodology and tools

Chronologically, the application of the scenario approach took shape in the late 1980s as an expected and reasonable alternative to univariate econometric forecasts of the future implementation of large-scale investment projects and the prospective development of transnational corporations. However, in essence, the scenarios read out at that time were prepared as tools for the implementation of a corporate strategy. In such scenarios, the emphasis was placed on precisely those positions that were deemed significant for most line managers of these structures and staff analysts during their current discussions of variable management decisions, taking into account the influence of a properly functioning feedback system, Russified and entered into everyday circulation as feedback.

These kinds of connections are extremely useful and preferable to others, provided that there is a sincere desire to know what really happened in the past and to learn from what was done then. And in order to choose a further path of development, the analyst-planner / planner-scriptwriter needs more or less reliable and complete information about the future – a kind of advanced connection with a given perspective, which is very conventionally demonstrated in Fig. 1.

Any event preference, when expressed in the form of utility, is combined with probabilities in a general theory of rational decisions called the decision theory, as follows: *Decision theory = Probability theory + + Utility theory*. It is appropriate here to recall the wisdom of the greats. Thus, Charles-Maurice de Talleyrand-Périgord used to say: “The art of managing public affairs is to foresee the inevitable and to facilitate its fulfillment.”[11]

The fundamental idea of decision theory is that any planner analyst is rational if and only if he chooses an action that allows him to achieve the greatest expected public utility, averaged over all possible outcomes of a given action. This forms the essence of the so-called principle of maximum expected utility (MEU). Univariate forecasts, as a rule, rigidly set a single trajectory for the future development of an organization and / or a sectoral department (ministry, profile committee, etc.). But in practice, they most often turned out to be erroneous, in particular because of the ambivalence of the customers of the forecast. Therefore, with a scenario approach for a specific object of research, it is customary to develop several closely probabilistic outcomes (occurrence of events), but noticeably contrasting options for the future development of the external environment of this object.

The task of the scenario method is to develop a certain common understanding in the team of the analyzed object, which will provide its personnel with coordinated actions in achieving the main strategic goals of the actor of the socio-economic space. The main goal of the strategic conversation scheme is to create and launch in the structures of the studied object the process of conscious penetration of employees into the essence of the strategizing procedure [1]. But a more detailed and constructive idea of the process of scenario modeling (planning) can be given by the generally accepted scheme of iterations[12], consisting of eight steps-stages as edited by the authors of the article, tied to the subject of PC and shown in Fig. 2.

[11] Source: URL: https: //citaty.su/aforizmy-i-citaty-sharlya-morisa-de-talejrana. (date of access: 31.12.2020).

[12] Попов С.А. Актуальный стратегический менеджмент. Видение – цели – изменения: учебно-практическое пособие / С.А. Попов. – Москва: Издательство Юрайт, 2016. – 447 с. – (Авторский учебник). – ISBN 978-5-9916-8216-9. – Текст : электронный // ЭБС Юрайт [сайт]. – URL: https://urait.ru/bcode/393975 (дата обращения: 16.02.2021).

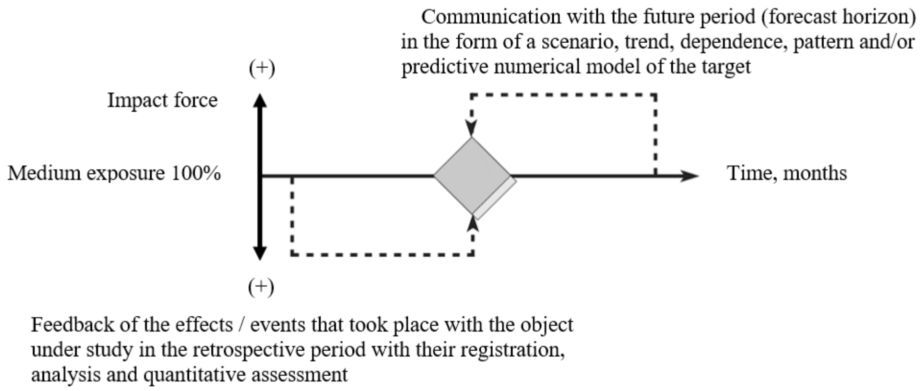

Fig. 1. Conditional scheme of relationships and influences of *feedback*-type effects on the analyst's scenario activity. Compiled by the authors

Nevertheless, it should be remembered that the scenario itself is noticeably different from the model forecast and subjective vision (almost always, desired and individual), but is a convincing description of the most plausible options for shaping the future. The diagram in Fig. 3 allows us to illustrate the differences between the three main categories of perception of future constructions of what is happening. Referring to the generally accepted planning terminology, developers constantly build their sets of actions on the object of study for the planned period, and these actions are most often based on various types of forecasts, scenarios and visions. In stable conditions and in a short time frame, socio-economic forecasts, as a rule, are both necessary and effective, since they allow reducing the considered risks [10], quantifying the complex of threats, and also increasing the certainty of the main events and effects that will occur in the coming periods with the analyzed industry – PC healthcare.

Ideally, each strategic decision in the scheme of the development strategy of the studied object as a whole should become sufficiently stable in any scenario created. But it is extremely difficult to come to such solutions of sufficiency, and in some cases, it is simply impossible. A more typical situation is when certain strategic decisions and / or development strategy of the industry as a whole turn out to be good (simplified semantics) under one or several specific scenarios and bad (semantics of the same level) when analyzing other scenarios.

Therefore, considering the developed scenarios, with a quantitative justification of certain decisions contained in them, for example, those outlined in stage 1, it is necessary to weigh the various risks associated with the probability of the occurrence of certain scenario events statistically. In addition, there should be a deliberate search for such precise strategic decisions that will be sufficient and acceptable for the object under study relative to all available scenarios.

One example of possible risks is the situation with the *Covid*-19 pandemic and its extremely grave consequences for the socio-economic situation not only in the regions, but also in the country as a whole. According to the Rospotrebnadzor for 12.12.2020, the total number of infected in PC reached 12 133. The indicator of the daily increase in patients reached 1.2%, which makes it possible to track the dynamics of the spread of infection in the region. The prevalence rate of the disease as of the indicated date was 1.19 (for comparison, 1.13 as of October 21, 2020)[13].

The large-scale socio-economic consequences of the pandemic have yet to be described by specialists, but it is already obvious today that the population has undergone a targeted strike. According to official data, excess mortality in Russia for eleven months of 2020 exceeded the corresponding period of the previous year by 230 thousand people[14]. According to the unconfirmed information of independent statistician

[13] Map of the spread of coronavirus in PC // URL: / www.permkrai.ru/antivirus. (date of access: 20.12.2020).
[14] Dissenting opinion of prof. Zubarevich N.V. URL: / https: //echo.msk.ru/sounds/2772800.html (date of access: 14.01.2021).

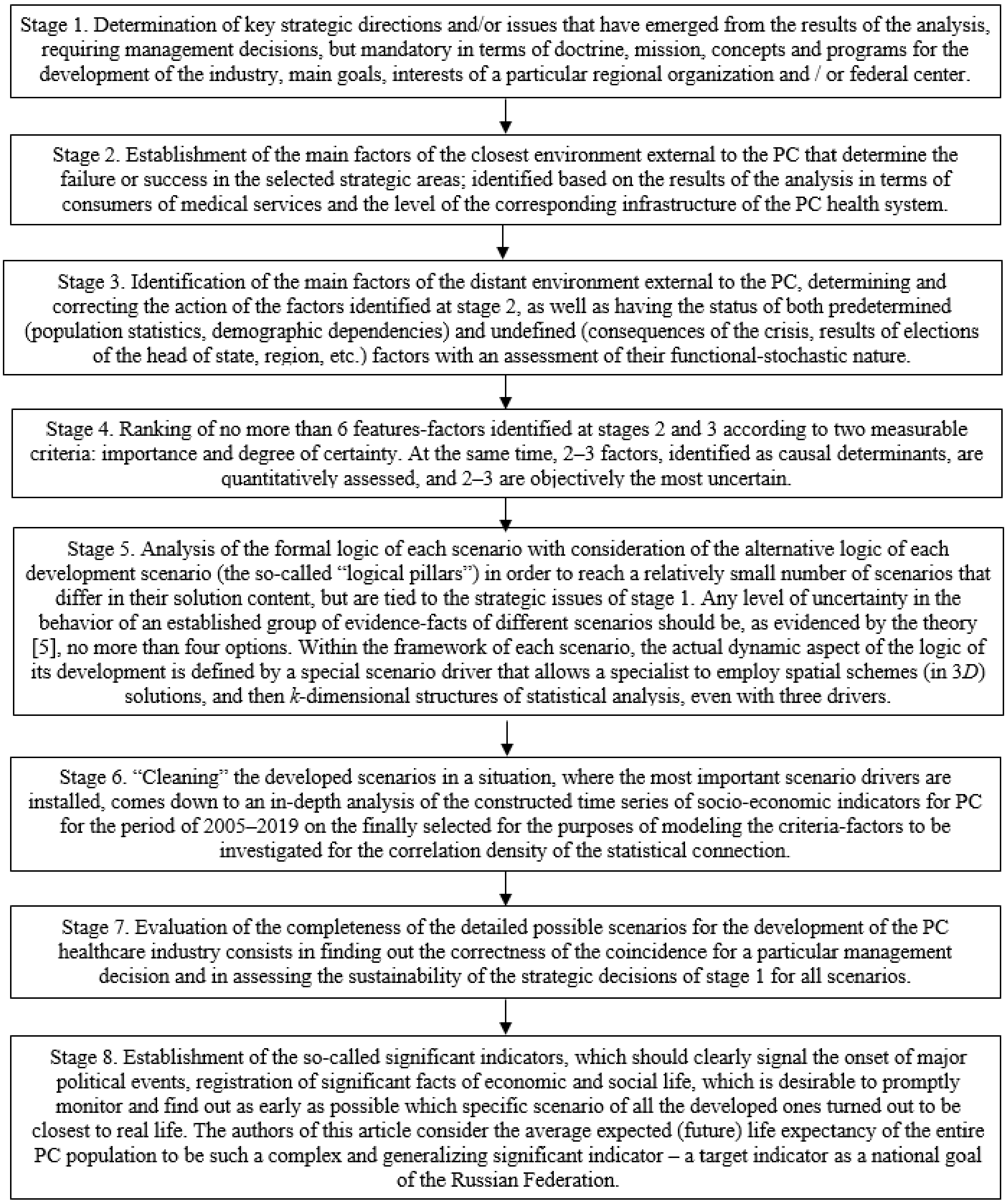

Fig. 2. Stages of the iterative procedure for developing scenarios for the development of the health care system of the Perm Territory for the period of 2020–2023. The standard steps for iterating the stages are given as edited by the authors of the article

A. Raksha (ex-demographer of Rosstat), excess mortality in the Russian Federation is even more significant and reaches as much as 300 thousand people.

More recent and updated information on the registration of deaths and births for April-October indicates a sharp increase in excess mortality compared to 2019 in the Russian Federation – + 16%, and for the so-called highlighted zones: in the first zone of "hard growth" in Moscow – + 26%; Moscow region + 22%; St. Petersburg 26%. In the second zone of "most severe growth": Dagestan – + 46%; Ingushetia + 48%; Chechnya – even + 53%. In November 2020, the statistics are condensed even more – in Moscow + 48.9%; in December, these figures for the capital and St. Petersburg and Leningrad Region are similar

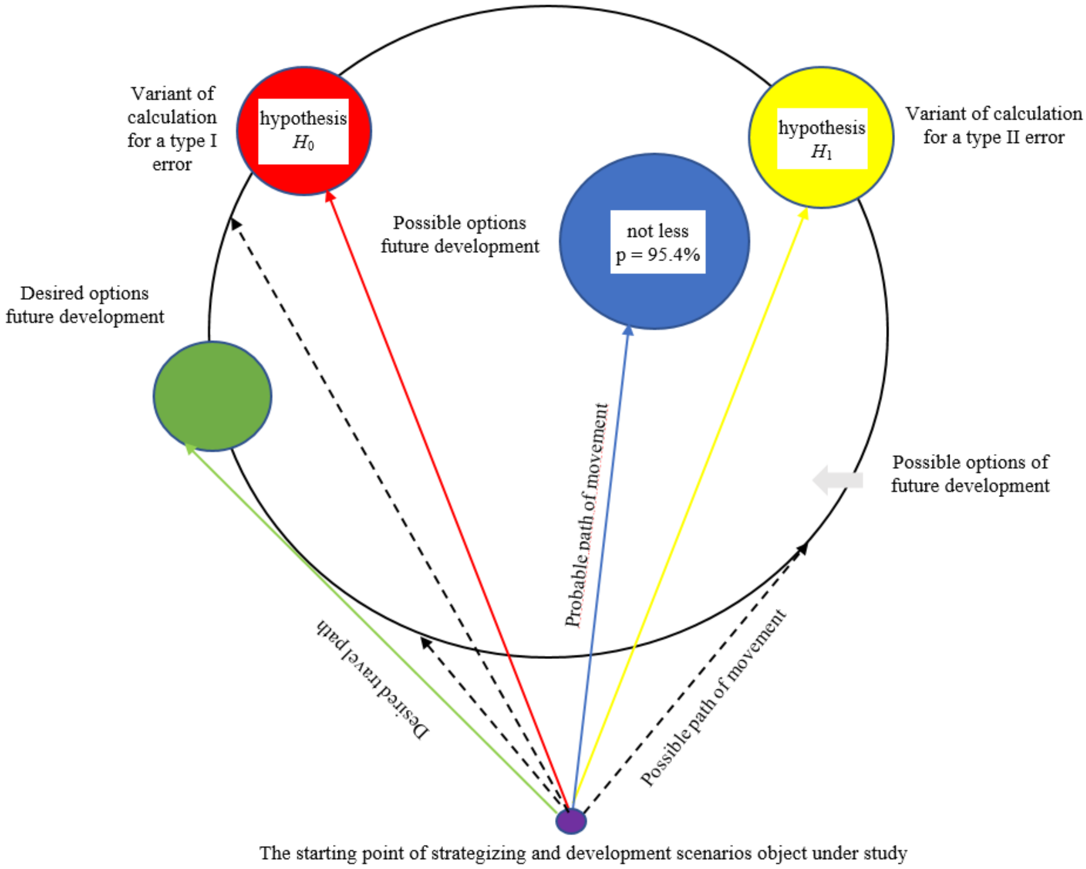

Fig. 3. The relationship between the desired, possible and probable variants of perception of the formed future.
The idea of the circuit design was borrowed by the authors from [5]

and are approaching 50 percent. Against this background, the situation in the PC by this indicator turned out to be much calmer[15].

At the same time, the population of the country is significantly decreasing, and at a noticeable pace: from January to September 2020, 1,069 thousand children were born, which is 47 thousand less than in 2019. During the same period, the natural population decline amounted to 387 thousand people against 150 thousand last year. The total population of the country decreased by 510 thousand people against 2020[16]. According to the same demographic statistician A. Rakshi, the decline even reached 590 thousand people[17].

The increase in mortality due to the pandemic will lead to the fact that life expectancy at birth by the end of the past year will certainly decrease. However, the Decree of the President of the Russian Federation of July 21, 2020 No. 474 "On the national development goals of the Russian Federation for the period up to 2030" in paragraph 2a) ("Preservation of the population, health and well-being of people") established a target indicator characterizing the achievement of national goals by 2030 as raising life expectancy to 78 years[18]. If some analysts estimate this indicator for 2019 at 73.3 years in the Russian Federation[19], then the results of 2020 can make their own noticeable adjustments, lowering it by several years at once. To revive

[15] Program "Aces" with prof. N.V. Zubarevich. URL: / https: //echo.msk.ru/sounds/2776966.html (date of access: 21.01.2021).
[16] Remchukov K. Personally yours. https://echo.msk.ru/sounds/stream.html (date accessed: 02/08/2021).
[17] In the circle of light. URL: https: //echo.msk.ru/sounds/stream.html (date of access: 09.02.2021).
[18] Decree of the President of the Russian Federation of July 21, 2020 N 474 "On the national development goals of the Russian Federation for the period up to 2030" // URL: https: //rg.ru/2020/ 07/22 / ukaz-dok.html ... (data obrashcheniya: 10.01.2021).
[19] RBC data // URL: https: //www.rbc.ru/society/16/12/2020/5fbd65c79a794747f677e904. (date of access: 14.01.2021).

the content of the article, it can be noted that at the beginning of 2021 there were more than 5 million people over 80 years old in Russia, and the country's internal affairs bodies even received instructional departmental proposals to store fingerprints for up to 100 years.

The hypothesis put forward by some experts that the main victims of the coronavirus are the elderly from different risk groups has not yet received its final confirmation from sanitary doctors and doctors. But the demographic fact is indisputable – the Russian population is aging. The theses that the age structure of the population does not depend on its size, and that it does not change over time, are considered preliminary by the authors of the article. The nonlinear trend of age-related mortality, i.e. the characteristics of mortality in each age group, differ markedly, depending on the territory of observation, the trend has not been identified in terms of the set of taken into account signs-factors and has not yet been found in open public models.

Thus, the listed theses can also be called working statistical hypotheses. Here, the calculation carried out by the United Nations Program for the Assessment of the Human Development Index (HDI) for Russia, using the structural average, *the median*, may seem useful. Thus, the median age in the country in 2010 was 38.0 years, and by 2020 it had grown to 39.6 years. This means that exactly half of the Russian population in the past year was younger than that age, and the other half was older. Another interesting research, in the context of the discussion, is the per-country estimate of excess mortality using their own original statistical model, which was built by *The Economist* analysts in the context of eliminating the impact of the *Covid*-19 pandemic on the natural population decline in the first row countries [18].

The implementation of the national project "Demography" alone after all adjustments would require the funding of 4.6 trillion rubles from 2019 to 2024. And 90% of the funds, something about 700 billion rubles, according to the Ministry of Finance of the Russian Federation, have already been spent on demography by the end of 2020[20]. Large-scale healthcare costs are always necessary, always appropriate, and almost always inevitable. But the assessment of the effectiveness of such investments can be measured using any complex, composite indicator or associated indicator that characterizes the productivity of investments in the industry under study quite reliably. The authors of the article, fully agreeing with the well-known thesis that "money does not heal", consider the average life expectancy of the entire population of the country (without division by gender) as such a universal indicator, as well as the subject of the federation, including a typical resident of the PC.

In the context of proper digitalization of processes, including demographic processes, improvement of statistical observation, accounting, analysis of fertility, mortality, migration and mechanical movement of the population, such an indicator turns into an indicator of early detection of the concomitant effects of targeted funding and administrative efforts on the ground in specific scenarios and in the field of the strategic competence of the relevant specific organization (say, the Administration and the Government of the PC). Such mastered professional competence in the field of strategizing, in turn, will become quite a solid basis for creating a powerful lever of power structures in the PC for making the necessary decisions, and, consequently, achieving a strategic competitive advantage at the interregional level of the Russian Federation.

The same professional competence will make it possible to carry out a systematic and complex analysis of the developed scenarios in an information environment with serious uncertainty in a qualified manner, taking into account the real-life effects of *emergence* and *synergy* inherent in the scenario. The system under study, for example, a health care management system in the PC alone, may have the property of emergence initially, but given and by default, in a situation when this system is made up of components built on the basis of local elements, which are not inherent in this system property of the system separately.

The property of synergy presupposes a varied interaction of the components of the system, as a result of which the system under study acquires new qualitative varying characteristics depending on the composi-

[20] Правительство вдвое сократило расходы на здравоохранение/ https://www.finanz.ru/novosti/aktsii/pravitelstvo-vdvoe-sokratilo-raskhody-na-zdravookhranenie-1030173928 (дата обращения: 27.02.2021).

tion of the components, which did not initially possess the formed property. These differences in the understanding of the essence of system properties suggest that a type I property is a dynamic derivative from the development of the system under study itself with a fixed set of components. Accordingly, emergence occupies a higher position in the hierarchy of systemic properties than synergy.

A common example is the description of emergent properties in the Bible, the Gospel of Matthew – "Because the Lord said: ... for where two or three are gathered in My name, there I am in the midst of them"[21]. An example of a synergistic property can be the joint action of individual authorities or system elements of the administrative vertical in the forced resolution of a serious problem that has arisen. Or a joint effect on the human body according to a specially prescribed scheme of various drugs, which enhances the healing effect of each of them.

Returning to the problems of financing efforts in healthcare in the PC, it should be noted that the method of raising funds in the region has developed a mixed scheme, which involves both personal funds of the population and state ones, i.e. public finance. The program of state guarantees of free provision of medical care to citizens (SGBP), investment costs, maintenance of medical institutions, including educational institutions, the activities of the sanitary-epidemiological service, etc. are financed at the expense of budget funds.

At the same time, the population of the region pays for medical care both directly, by paying for medical services in state, municipal and private organizations, and through voluntary medical insurance schemes (VHI). The named features of financing can be taken into account in the scenario approach in the course of statistical modeling using traditional and well-known techniques. Modeling difficulties can cause blurred measurements of various kinds of consequences of the gathering strength of the *Covid*-19 pandemic with its many predicted *waves* already throughout 2021.

Results

With the agenda of improving the efficiency of managing a commercial organization and / or administrative (power) structure in the newest conditions, the well-known information and analytical agencies *Deloitte* and *Salesforce* organized an international discussion on the development of scenarios for the development of events with some of the world's best experts in scenario planning to study the impact of the current situation on politics, society and business [3]. As a result of a professional discussion, specialists proposed for consideration four detailed scenarios for the long term (3–5 years): what will the world look like after the coronavirus and what will organizations and economic entities need to safely continue their normal activities in the new conditions? All scenarios mentioned on the forum were created using modeling capabilities.

Construction of an economic and statistical model for the analysis and forecast of the dynamics of the efficient feature

When using systematic statistical methods for evaluating high-dimensional models, consisting of a system of structural equations, quite reliable prospective calculations of interrelated effective signs-factors can be made, even those suffering to a certain extent with the effect of multicollinearity (interdependence, joint dependence of variables) on the forecast horizon from 3 to 5 years [7]. In general, each such structural equation is a dynamic multivariate model (DMM) with a trend component.

The authors of the article used in their research a modification of the V.V. Shvyrkov – A.N. Tsatsulin[22] for constructing the DMM of the upcoming (expected) average life expectancy of the entire PC population from the features-factors taken into account in the work, formed within the health care system of the studied subject. The mentioned system in general form and in generally accepted standard notation can be written in a matrix form as follows:

[21] Bible. Books of Holy Scripture of the Old and New Testaments with parallel passages and appendices. Ch. 18, verse 20 – Moscow: Eksmo Publishing House, 2018. – 771 p. ISBN: 978-5-04-089852-7

[22] Tsatsulin A.N. Primeneniye statisticheskikh metodov pri modelirovanii i kratkosrochnom prognozirovanii razvitiya otrasli (na materialakh konditerskoy promyshlennosti RSFSR) // Dissertatsiya na soiskaniye uchonoy stepeni kandidata ekonomicheskikh nauk / Leningradskiy finansovo-ekonomicheskiy institut im. N.A. Voznesenskogo. Leningrad, 1974. – 228 s.

$$y_h^{(t_i)} = Y\gamma + X_1\beta + \varepsilon_{ht_i}, \tag{1}$$

where $y_h^{(t_i)}$ are the efficient h-variables that are influenced by interdependence at time t_i;

Y is a matrix of effective features from individual structural equations of the system in the i^{th} year;

X_1 is a matrix that includes a set of exogenous and endogenous variables with the identified corresponding time lag;

β, γ are parameters for dependent and independent variables of multiple regression equations;

ε_{ht_i} is a vector of residual random component for each h-variable.

The system from expression (1) can also be written through the so-called reduced form for endogenous variables $y_h^{(t_i)}, h = \overline{1,m}$ with zero lag as a system of linear *simultaneous* equations for predefined variables (exogenous and endogenous with lag) and random components of the form ε_{ht_i}. Here, we assume that none of the constructed equations can be expressed as a linear function of the others, since otherwise, one equation would be redundant and the system of equations would be inconsistent. The given form is as follows:

$$y_h^{(t_i)} = \Theta_h Z_h + \eta_{ht_i}, \tag{2}$$

where Z_h is the $[1 \times m]$ matrix of predefined variables;

Θ_h is a matrix of linear regression coefficients with dimension $[1 \times m]$;

η_{ht_i} is the random component of the already reduced form, which is a linear function of the magnitude of the statistical "residual" ε_{ht_i}.

Regression y_h for all characteristics Z_h can be obtained using the method of least squares (OLS-estimates; *The Method of the Least Squares* – LS) as coefficients of the reduced form Θ_h. The OLS estimates of each equation in system (1) may not represent true estimates of structural coefficients at all. The meaning of the reduced form of the model in this case is that the individual equations that make up the model system can be interpreted as conditional mathematical expectations (MEM), or operator **E** on endogenous variables, provided $\text{E} = \left(\eta_{ht_i}\right) = 0$.

The advantage of the reduced form for forecasting purposes is that its constituent equations express unidirectional relationships between variables. The predefined variables in this case affect the interdependent variables; the inverse statistical effect in the recursive mode is excluded. When forecasting complex socio-economic processes, both of the listed types of models are used in their classical form – recursive and interdependent equations.

Consider the part of the abbreviated form that corresponds to the jointly dependent variables on the right side of expression (1). Estimating it using OLS, it turns out

$$Y = X\left(X^*X\right)^{-1} X^*Y + U, \tag{3}$$

where $\left(X^*X\right)^{-1} X^*Y$ is the matrix of coefficients of the reduced form, obtained with the help of OLS estimation, in its it meaning corresponds to Θ_h from Eq. (2);

* is a sign of transposition of matrix X;

U is a matrix of random residuals of the system $U = \left\{\eta_{ht_i}\right\}$.

Let us list the stages of constructing structural equations, each of which is a DMM.

1. Since the most effective methods (from those described in the literature) for assessing the statistical relationship have been developed in relation to linear dependencies, and the real dynamics of the socio-economic process is usually described more successfully by nonlinear functions of a multiplicative and power-law form, the initial information for all variables is dependent and independent (pre-selected and analyzed from the point of view of the closeness of the statistical relationship), is subjected to logarithm to the base of the natural logarithm, followed by the calculation of the first differences of the index

series. This operation further enhances the random nature of the distribution of chain indices. That is, the calculation is carried out

$$\ln\left\{Y_{jk}^{(i)}\right\} - \ln\left\{Y_{jk}^{(i-1)}\right\} = \left\{y_{jk}^{(i)}\right\}; \quad \ln\left\{X_{jk}^{(i)}\right\} - \ln\left\{X_{jk}^{(i-1)}\right\} = \left\{x_{jk}^{(i)}\right\}. \tag{4}$$

2. At the second stage, to take into account the aggregated features-factors in dynamics and exclude autoregression from the corresponding values of chain indices $\left\{y_{jk}^{(i)}\right\}, \left\{x_{jk}^{(i)}\right\}$, obtained by the formulas from Eq. (4), time trends are excluded. At the same time, analytical alignment is carried out over two homogeneous periods from the point of view of the characteristics of the development of regional health care (different configuration of time trends), in the specific case of the dynamics of meso-indicators of PC: those are 2005–2008 and 2009–2019. With a more preferable length of the time series system (say, from 1991 to 2020) and under specific conditions of periodization of dynamics, the number of sub-periods identified can be greater. The aggregates of residual deviations from their time trends in the form of linear functions are marked from above with the mathematical sign "wave" (~, i.e. the upper tilde):

$$\left\{y_{jk}^{(i)}\right\} - \left\{y_{jk}\left(t_i\right)\right\} = \left\{\tilde{y}_{jk}^{(i)}\right\}; \quad \left\{x_{jk}^{(i)}\right\} - \left\{x_{jk}\left(t_i\right)\right\} = \left\{\tilde{x}_{jk}^{(i)}\right\}. \tag{5}$$

3. At the third stage, there is the estimation of the degree of linear correlation of residual deviations from time trends in subsets from Eq. (5) and calculation of the so-called net coefficients of elasticity $\{a_{jk}\}$ in the equations of multiple regression of the dependent variable on explanatory variables as a column matrix of regression parameters.

At this stage, various estimation methods are applied and sequentially analyzed-generalized OLS according to Aitken A.C. [10], in which the covariance matrix of the vector of random variables is estimated, and two-step OLS according to H. Theil [8, 15], by which the reduced form is simultaneously estimated. Individual dependencies are preliminarily evaluated as equations belonging to the recursive system.

Although these estimates $\left\{\mathrm{E}\left[LS\left(a_{jk}\right)\right]\right\}$ are not fully *consistent* and *unbiased*, they nevertheless give a general idea of the order of magnitude of the pure coefficients of elasticity, therefore their calculation is very useful as characteristics of the comparative sensitivity of variability of features-factors. At the same time, on their basis, it is possible to obtain the values of the coefficients of determination for each of the structural equations to clarify the *explained* variability of the features-factors taken into account in the modeling.

4. At the fourth stage, each structural equation of the model provides elements of dynamism not only by introducing time trends into the model, but also by aggregated factors (for example, the official percentage of excess mortality under *Covid*-19, drug pricing, deepening of the economic crisis, inflation expectations [22] transfers from the federal budget, etc.), taken into account at this stage by the authors of the article using a special method.

5. Calculations of the fifth stage provide for the calculation of special statistical indicators and criteria for the reliability of the parameters of the model based on deviations from Eq. (5), and verification of statistical tests and hypotheses: the normalized coefficient of multiple correlation for the entire retrospective period $\left(\overline{R}_m\right)$; coefficient adjusted for the random sample size $\left(\hat{R}_m\right)$; R. Fisher's corrected theoretical ratio $\left(\hat{F}_{meop}\right)$; empirical Durbin-Watson test (DWэ). These estimates involve intermediate calculations for the 3rd and the 4th stages of modeling.

6. At the sixth stage, the forecast values of the variables are verified (a set of indicators for the development of the health care system and population statistics) given by the model based on the actual data of years of the quasi-retrospective period, i.e. for the years that have already been reported. Such a check reveals (or not) the appropriate predictive capabilities of the model for each of the scenarios considered in this study. Thus, the proposed model for analyzing and forecasting the expected (upcoming) average life

expectancy of the entire PC population can successfully serve as a tool for prescheduled calculations for 2021–2023 and development of a strategy for the development of the health care system of the studied federal subject for a more significant perspective.

7. At the seventh and last stage, when various values of predetermined (mainly exogenous) variables are introduced into the corresponding structural equation, they can be "played" by the capabilities of information technologies on good-quality application packages of the latest generations such as *SPSS*-16 and *Statistica*-11 forecast options for the constructed model in the general structural shell. Further, the optimal scenario of development from the point of view of the successful functioning of the studied healthcare system is selected. When setting the variant values of variables for the forecast horizon, it is advisable to involve expert assessments of relevant specialists as an auxiliary material in measuring the ranks and ratings of risks [17] and threats.

Carrying out calculations at the last stage, it should be borne in mind that the assignment of alternative options for values for a number of variables associated with the creative planning-variative activity of PC controls allows you to quantitatively measure the comparative effectiveness of individual levers of programs, concepts and strategies of the socio-economic development of the territory and their cumulative impact on the life expectancy of an average Permian. It is not only the main socio-economic indicator of the development of the territory, but also the target indicator, as well as the national goal.

Let us list the endogenous and exogenous variables, used in this modeling content, with their conventions:

$y_{1,1}^{(i)}$ – Budget revenues of a constituent entity of the federation (PC) in current prices in the i^{th} year;

$x_{1,1}^{(i)}$ – Gross regional product (GRP) of the region in current prices in the i^{th} year;

$x_{1,2}^{(i)}$ – Tax revenues to the regional budget at current prices in the i^{th} year;

$x_{1,3}^{(i)}$ – SME turnover in comparable prices in the i^{th} year;

$y_{2,1}^{(i)}$ – Expenditures of the regional budget for the development of the health care system in comparable prices in the i^{th} year;

$x_{2,1}^{(i)}$ – The volume of funds of the regional VHI system in comparable prices in the i^{th} year;

$x_{2,2}^{(i)}$ – The size of the PC budget deficit in comparable prices in the i^{th} year;

$x_{2,3}^{(i)}$ – The average annual population of the PC in the i^{th} year according to the official statistical reporting until 2019[23];

$y_{3,1}^{(i)}$ – Expenditures for the development of the PC healthcare infrastructure in comparable prices in the i^{th} year;

$x_{3,1}^{(i-1)}$ – Interbudgetary targeted transfers in comparable prices in the previous i^{th} year;

$y_{4,1}^{(i)}$ – Contributions to the OMS PC fund in comparable prices in the i^{th} year;

$x_{4,1}^{(i)}$ – The level of general morbidity in the region in the i^{th} year;

$x_{4,2}^{(i)}$ – The volume of paid medical services for the PC in comparable prices in the i^{th} year;

$x_{4,3}^{(i)}$ – Comparative index of retail prices for medicines and medicines from the List of vital and essential medicines for medical use[24] in the retail and hospital network of the PC in the i^{th} year;

$y_{5,1}^{(i)}$ – The upcoming (expected) average life expectancy of the region's population in the i^{th} year;

[23] The indicator of the average annual number in the PC is taken into account, since all the characteristics of natural population decline are assessed precisely against this initial base.

[24] Decree of the Government of the Russian Federation of August 12, 2020 No. 1212 "On Amendments to the Rules for the Formation of Lists of Medicines for Medical Use and the Minimum Range of Medicines Required for the Provision of Medical Care". URL: https://www.garant.ru/products/ipo/prime/doc/74411004/ (date accessed: 01/10/2021).

$x_{5,1}^{(i)}$ – The birth rate in the region in the i^{th} year;

$x_{5,2}^{(i)}$ – The mortality rate in the region in the i^{th} year;

$x_{5,3}^{(i-1)}$ – Infant mortality rate[25] in the region, that is, throughout the territory of the subject of the federation the Perm Territory, in the previous i^{th} year[26].

Let us give a schematic architecture of the linearized structural equations of a complex of dynamic multifactorial models of the development of the PC health care system in the statistical assessment by systemic methods, namely, DMSS, for the specified retrospective period 2005–2019 with periodization of the dynamics by a system of coupled time series with verification for 2020 and a random component ξ_{h,t_i} for each individual isolated equation from the system.

1. Budget revenues of the studied subject of the Federation (Perm Territory):

$$\underset{}{y_{1,1}^{(i)}} = \underset{(0.00587)}{a_{1,0}} + \underset{(0.711)}{a_{1,1}x_{1,1}^{(i)}} + \underset{(0.679)}{a_{1,2}x_{1,2}^{(i)}} + \underset{(0.951)}{a_{1,3}x_{1,3}^{(i)}} + \underset{(-0.00174)}{a_{1,t}\left(t_i - \bar{t}_i\right)} + \xi_{1t_i},$$

$$\overline{R}_m = 0.8815;\ \hat{R}_m = 0.8417;\ \hat{F}_{теор} = 1.41;\ DW_Э = 2.03. \tag{6}$$

2. Expenditures of the regional budget for the development of the health care system:

$$y_{2,1}^{(i)} = \underset{(0.00302)}{a_{2,0}} + \underset{(1.297)}{a_{2,1}y_{1,1}^{(i)}} + \underset{(-1.124)}{a_{2,2}x_{2,1}^{(i)}} + \underset{(-1.876)}{a_{2,3}x_{2,2}^{(i)}} + \underset{(0.0217)}{a_{2,4}x_{2,3}^{(i)}} + \underset{(-0.00544)}{a_{2,t}\left(t_i - \bar{t}_i\right)} + \xi_{2t_i},$$

$$\overline{R}_m = 0.9475;\ \hat{R}_m = 0.9308;\ \hat{F}_{теор} = 1.15;\ DW_Э = 2.09. \tag{7}$$

3. Expenditures for the development of the regional healthcare infrastructure:

$$y_{3,1}^{(i)} = \underset{(0.00176)}{a_{3,0}} + \underset{(0.732)}{a_{3,1}x_{1,1}^{(i)}} + \underset{(0.301)}{a_{3,2}x_{3,1}^{(i-1)}} + \underset{(1.126)}{a_{3,3}y_{1,1}^{(i)}} + \underset{(0.434)}{a_{3,4}y_{2,1}^{(i)}} + \underset{(0.00598)}{a_{3,t}\left(t_i - \bar{t}_i\right)} + \xi_{3t_i},$$

$$\overline{R}_m = 0.9593;\ \hat{R}_m = 0.9418;\ \hat{F}_{теор} = 1.13;\ DW_Э = 1.94. \tag{8}$$

4. Contributions to the regional compulsory medical insurance fund:

$$y_{4,1}^{(i)} = \underset{(0.00319)}{a_{4,0}} + \underset{(0.776)}{a_{4,1}y_{3,1}^{(i-1)}} + \underset{(0.802)}{a_{4,2}x_{4,1}^{(i)}} + \underset{(0.486)}{a_{4,3}x_{4,2}^{(i)}} + \underset{(0.612)}{a_{4,4}x_{4,2}^{(i-1)}} + \underset{(0.877)}{a_{4,5}x_{4,3}^{(i)}} +$$

[25] In the Volga Federal District, the PC in terms of infant mortality, i.e. the number of children who died before the age of 1 year per 1,000 live births was 4.7 ‰ in 2018, and 5.2 ‰ a year earlier. In 2019, the indicator dropped to 4.6 ‰, but it is significant that 65.90% of the total number of babies who died before the age of one year were children of the first month of life [26]. In the countryside, this indicator is much higher. In recent years, the methodology for calculating the infant mortality rate $K_{\text{inf}.mort}$ has undergone certain changes. Now this coefficient is measured as the sum of two components: the first is the ratio of the number of deaths up to a year in the current year $\left(m_1^{(1)}\right)$ from the generation of those born in the current year to the total number of those born in the considered year (N_1); the second is the ratio of the number deaths under one year in the current year from the generation of those born in the previous year $\left(m_1^{(0)}\right)$ to the total number of births in the previous year (N_0): $K_{\text{inf}.mort} = \frac{m_1^{(1)}}{N_1} + \frac{m_1^{(0)}}{N_0}$.

[26] The program "Development of children's health care in the Perm region, including the creation of a modern infrastructure for the provision of medical care to children". Approved by the Resolution of the Government of the Perm Territory dated June 17, 2019 No. 411-p. http://docs.cntd.ru/document/561434147 (date accessed: 02/08/2021).

$$+ \quad a_{4,t}\left(t_i - \bar{t}_i\right) \quad + \quad \xi_{4t_i},$$
$$\left(-0.00072\right)$$

$$\overline{R}_m = 0.9336; \quad \hat{R}_m = 0.8953; \quad \hat{F}_{теор} = 1.26; \quad DW_Э = 1.82. \qquad (9)$$

5. The upcoming (expected) average life expectancy at birth for the entire population of the region:

$$y_{5,1}^{(i)} = a_{5,0} + a_{5,1}y_{4,1}^{(i-1)} + a_{5,2}y_{3,1}^{(i-1)} + a_{5,3}y_{2,1}^{(i)} + a_{5,4}x_{5,1}^{(i)} + a_{5,5}y_{5,1}^{(i-2)} +$$
$$(0.00411) \quad (0.523) \quad (0.621) \quad (0.194) \quad (0.461) \quad (-0.543)$$
$$+ \quad a_{5,6}x_{5,2}^{(i)} + a_{5,7}x_{5,3}^{(i-1)} + a_{5,t}\left(t_i - \bar{t}_i\right) + \xi_{4t_i},$$
$$(-0.628) \quad (-0.124) \quad (-0.00102)$$

$$\overline{R}_m = 0.823; \; \hat{R}_m = 0.789; \; \hat{F}_{теор} = 1.03; \; DW_Э = 1.28. \qquad (10)$$

Discussion

Depending on the chosen development scenario, a three-year plan for improving the infrastructure of the region, providing for the development of more than 8 billion RUB budget funds and the commissioning of 24 healthcare facilities by the end of 2023 may be subject to significant adjustments. So, the optimistic version of the development of the system will allow the restoration of the previous specialized emergency teams, including cardiology, to those that remained in conditions of limited funds and a pandemic – linear, intensive care, children, etc. psycho-brigades. The medical personnel of the ambulance service from the units, operating at the end of 2020 are simply not able to provide assistance in serious cases: clinical deaths, pulmonary edema, road accidents, heart attacks. The number of calls per day dropped[27]. Adjustment of scenarios may even affect facilities built in the PPP regime over the years.

2021: Surgical building of the hospital, Tverie; Hospital for Infectious Disease; New building of the regional oncologic dispensary; Medical building in Cherdyn; Medical building with a polyclinic in S. Yurla; Children's polyclinic in Kudymkar; City Clinical Polyclinic in Perm; 3 children's polyclinics in Perm.

2022: Children's polyclinic in Perm (Motovilikhinsky district); Regional hospital complex in Polazna settlement; Children's polyclinic in Tchaikovsky; Polyclinic in S. Siwa;

2023: Hospital of the regional psychiatric hospital in Perm; Surgical complex in Kudymkar; Psychoneurological dispensary in Perm; Polyclinic phthisiopulmonary building in Perm; Medical diversified building in Perm.

With the total amount of funds allocated for three years under the optimistic scenario of the development of the healthcare system in the amount of 180 billion RUB, the number of doctors per 10 thousand of the population of the region will be 37.8, which by the end of 2023 will exceed the level of provision in the Volga Federal District (with the respective number of 36.1) and even in the Russian Federation (at the level of 37.6). At the same time, the Program envisaged to increase payments to zemstvo doctors and zemstvo paramedic by about 2 times in comparison with 2020 (up to 2 million RUB and 1 million RUB, respectively) in the framework of the same optimistic scenario for the development of the PC health care. The universal indicator of the improvement of the health care system (target indicator) chosen by the authors of the article in their study made it possible to simulate predictive calculations in Eq. (10) for three selected scenarios for the period of 2021–2023, which is reflected in Table 2. For comparison, in the northern capital, it is envisaged to finance the city health system and the pharmaceutical industry in the amount of 122 billion RUB only for 2021, which exceeds 16.0% of all expenses, however, there is a deficit budget of the federal subject.

[27] URL: https://59.ru/text/health/2020/12/30/69672816/. (date of access: 18.01.2021).

Table 2. Dynamics of the expected (future) life expectancy at birth of the entire population of the Perm Territory when modeling a scenario forecast for the period 2020–2023

No. p/p	Name indicator	Forecast scenario		
		pessimistic*	optimal (successful)**	optimistic***
1	2	3	4	5
1	Life expectancy at birth, years 2020 (Born 1947) year	73.2	73.9	74.4
2	2021 (Born 1948) year	73.2	73.9	74.5
3	2022 (Born 1949) year	73.1	74.0	74.5
4	2023 (Born 1950) year	73.2	74.1	74.6
5	p-values at 5% significance level	0.000347	0.000211	0.000076
6	The coefficient of determination according to the model from Eq. (10) $d^2_{y_{5,1}}$, %	67.73	68.91	68.35
7	Standard error, %	0.307043	0.312874	0.313950
8	The autocorrelation coefficient of the residual values r_a	–0.24754	–0.23965	–0.24113
9	Empirical Durbin-Watson coefficient DW_{emp}	2.7133	2.45321	2.54498

Note:
– the number of observations n = 16, taking into account the year used for verification;
– scenarios in relation to this indicator can be conventionally named as options: * “Kazakh”; ** “Belarusian”; *** “Latvian”.

Conclusions

According to the authors of the article, scenario modeling gives a chance to increase the sustainability and improve the flexibility of business design for almost any business structure and management system. But even an economic-statistical model of a sufficiently large dimension, however, which does not possess the declared flexibility to the external and internal habitat of the object under study, will be characterized by excessive resource intensity, adjusted for crisis circumstances, and increased vulnerability to threats and risks.

Optimally flexible models of the corresponding variant of the scenario approach, on the contrary, significantly increase the possibilities and effectiveness of strategizing, since they do not exclude delays in making those managerial decisions that are fatal for the PC population. The authors believe that scenario forecasts of the functioning of the mechanism for managing the national health care system and measures to increase the average life expectancy of Russians belong to such managerial decisions of the national level. However, we should admit that the proposed model of life expectancy does not include the factors of influence of the *Covid*-19 pandemic, which will certainly lower the predictive estimate of the target.

During the first part of the research, the authors chose the following:

1. Health care was selected as the most balanced indicator of improvement and effectiveness (in terms of the speed of its manifestation) of the functioning of any system, be it federal or regional. The average expected (future) life expectancy of a Russian was studied as such an indicator.

2. A multistep algorithm for the implementation of the scenario approach was reasonably chosen when developing three options (under the influence of a multitude of taken into account signs-factors) of the development of the research object and making an appropriate managerial decision on a particular financial-economic and / or socio-economic situation / problem (Fig. 2).

3. In the course of the correlation-regression analysis and assessment of the measure of the closeness of the statistical connection, a group of features-factors under consideration, interdependent and forming the level of technical, economic and demographic indicators of the studied region for the period 2005–2019, was selected. The list of the features-factors selected for modeling, including those with the set time lag, is given on pp. 25–26.

4. Five equations of multiple regression were constructed according to the modified method of V. Shvyrkov–A. Tsatsulin, which were combined into a system representing a single dynamic multifactor model of the main indicators of the development of the PC healthcare industry. The numerical parameters of the conditionally independent parameters of this model on p. 26 show how the net elasticity coefficients were estimated using the two-step least squares method (LLS) based on the advanced SPSS-16 software package.

5. Based on the results of statistical multivariate modeling and forecasting in the medium term, estimates of the target indicator and the national goal, the expected (future) life expectancy of the PC population, were established as a balanced indicator in this study. The calculation results are presented in Table 2.

Directions for further research

In continuation of this study, the authors of the article suggest the following.

First, after waiting for the official statistics of meso economic indicators for the PC for 2020, they will first carry out verification comparisons of predictive calculations using the author's model from a system of five simultaneous dynamic equations of multiple regression of linear forms from expressions (6) ÷ (10). If necessary, the net elasticity coefficients will be adjusted for independent variables, and already with the adopted amendments, the forecast of the main characteristics of the PC territory for the another impending three years will be made within the framework of the scenario approach to the development of the regional health care system, taking into account its specifics.

Secondly, the study of the impact and consequences of the *Covid*-19 pandemic on the PC economy is of particular interest to the authors of the article. For 17 months of attention to the coronavirus infection, that ruined Russian open spaces, a rich and interesting statistical material has already been accumulated. The authors intend to skillfully and correctly analyze this database in order to improve the methods and technologies of strategizing when using the scenario approach for making certain management decisions.

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THE IMPORTANCE OF EFFECTIVE EXTERNALIZATION WITHIN THE SECI MODEL FOR ORGANIZATIONAL DEVELOPMENT: ANALYSIS BASED ON GAME THEORY

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In the era of knowledge economy, knowledge is gradually replacing land, labor and capital as the main resource of economic development, the source of innovation, and the foundation for forming the major competitiveness of organizations. Organizational knowledge can be divided into explicit knowledge and tacit knowledge. Explicit knowledge can be stored and transmitted through information and network technology, while tacit knowledge must rely on the interaction between people and the organization to achieve the results of transmission, sharing and effective conversion. The effective management of tacit knowledge has an important influence on sustainable development of the organization. The main goal of this article is to improve the efficiency of sharing and conversion of tacit knowledge within the organization. In the research on tacit knowledge management, the SECI model of tacit knowledge conversion proposed by Nonaka is designed to convert tacit and explicit knowledge into each other through the process of socialization, externalization, combination and internalization. This cyclical conversion has formed a spiraling process of knowledge innovation, which provides a model and theoretical basis for the effective management and utilization of tacit knowledge. Through the SECI model we can find that in the process of externalization, the members of the organization and the organization itself convert tacit knowledge into explicit knowledge. In this process, the overall major competitiveness of the organization has been enhanced, but for the members of the organization as the subject of tacit knowledge, it may mean the loss of their core value. From the economic perspective, these mutual relations essentially reflect the conflict between the interests of individuals and organizational interests. Therefore, a mathematical model can be created from the perspective of game theory to study the problem concerning knowledge conversion within the organization, which is aimed at the prisoner's dilemma, as well as to design the incentive mechanism of tacit knowledge conversion within the organization for the purpose of changing the strategic equilibrium and realizing the effective management of tacit knowledge in the organization.

Keywords: tacit knowledge, SECI model, tacit knowledge management, game theory, organizational development, incentive mechanism

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ВАЖНОСТЬ ЭФФЕКТИВНОЙ ЭКСТЕРНАЛИЗАЦИИ В МОДЕЛИ SECI ДЛЯ РАЗВИТИЯ ОРГАНИЗАЦИИ: АНАЛИЗ НА ОСНОВЕ ТЕОРИИ ИГР

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В эпоху экономики знаний, знания постепенно заменяют землю, труд и капитал в качестве основного ресурса экономического развития, источника инноваций и основы для формирования ядра конкурентоспособности организаций. Организационные знания можно разделить на явные и неявные. Явные знания могут храниться и передаваться с помощью информационных и сетевых технологий, в то время как неявные знания должны полагаться на взаимодействие между людьми и организацией для достижения результатов передачи, совместного использования и эффективного преобразования. Эффективное управление неявными знаниями оказывает важное влияние на устойчивое развитие организации. Цель этой статьи - повысить эффективность совместного потребления и преобразования неявных знаний в организации. В исследовании управления неявным знанием модель преобразования неявного знания SECI, предложенная Нонака И., заключается в преобразовании неявного знания в явное и наоборот посредством процесса социализации, экстернализации, комбинации и интернализации. Эта циклическая трансформация сформировала спиральный процесс инноваций в области знаний, который обеспечивает модель и теоретическую основу для эффективного управления и использования неявных знаний. С помощью модели SECI мы можем обнаружить, что в процессе экстернализации организация и ее члены осуществляют преобразование неявного знания в явное. В этом процессе общая основная конкурентоспособность организации повысилась, но для членов организации как объекта неявного знания это может означать потерю своей основной ценности. С точки зрения экономики, эти взаимоотношения, по существу, отражают конфликт между индивидуальными интересами и интересами организации. Таким образом, можно создать математическую модель с точки зрения теории игр для изучения проблемы преобразования неявного знания внутри организации, нацеленной на дилемму заключенного, а также для разработки механизма поощрения преобразования неявного знания, чтобы изменить стратегическое равновесие и реализовать эффективное управление неявными знаниями в организации.

Ключевые слова: неявное знание, модель SECI, управление неявным знанием, теория игр, развитие организации, механизм поощрения

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Introduction

World Economic Forum held in Davos in 2016 introduced the concept of the *Fourth Industrial Revolution*. The Fourth Industrial Revolution relies on artificial intelligence, big data and the Internet, considers the development of science and technology as an important force for economic growth, formation of Industry 4.0 leads to growth of knowledge economy [1]. Knowledge-based and technology-based enterprise organizations are adapted to the needs of the Fourth Industrial Revolution and become a new growth point for the country's economic development in the future. From the perspective of knowledge management, improving the core competitiveness of organization has also become the focus of scholars. In the era of knowledge economy, knowledge has become the main production factor that promotes economic growth. There are many categories of knowledge. From the perspective of epistemology, knowledge is divided into explicit knowledge and tacit knowledge. Since Michael Polanyi proposed the concept of tacit knowledge in 1958, different scholars have carried out research on tacit knowledge from different fields. Research on tacit knowledge points out that tacit knowledge accounts for 90% of all knowledge in any organization [2], and knowledge that can be expressed in words and numbers is only the tip of the entire knowledge iceberg. At the same time, according to the modern strategic theory, the competition of enterprises has gradually evolved into competition of knowledge capital, knowledge as a strategic factor in accomplishing a sustainable competitive advantage is regarded as power [3]. Especially tacit knowledge capital, which is not only an important foundation for organization members to maintain their competitiveness, but also a core resource for organizations to create competitive advantages. A research based on externalization shows that knowledge is the most important piece of business competitive advantage and that tacit knowledge is a key part of that knowledge [4]. It can be seen that the effective management of tacit knowledge within an organization plays a vital role in improving the core competitiveness of knowledge-based and technology-based organizations.

The purpose of this paper is to establish a game model for organizations and employees by externalizing tacit knowledge based on the summary of the different tacit knowledge characteristics. In the game process, we can simulate the behavior of the organization and employees as well as analyze the reasons for inefficient conversion of tacit knowledge into explicit knowledge within the SECI model. In response to the phenomena, the authors further propose recommendations for the organization to establish incentive mechanisms in the process of externalization, so that the SECI knowledge creation model can have more practical application value in the development of high-tech and knowledge-based organization.

Research methods

The instrumental basis of this paper is the method of literature research and game theory model. One basic condition for organization to effectively manage tacit knowledge is to externalize the tacit knowledge of employees. In this process, there is a prisoner's dilemma involving provision of public goods by private individuals. This article establishes a repeated dynamic game model on this issue, and discusses the conversion of tacit knowledge under the Nash equilibrium from the perspective of employees' personal payoffs and overall payoffs of organization.

The concept and characteristics of tacit knowledge

Based on the problems covered in this article, we mainly focus on Polanyi's knowledge classification, namely explicit knowledge and tacit knowledge. Polanyi believed that explicit knowledge is a type of knowledge that can be expressed with various explicit symbols, i.e., in words, diagrams, and mathematical formulas. Tacit knowledge can be defined as skills, ideas and experiences that people have, it is non-codified and is difficult to express [5]. Explicit knowledge is information that can be expressed in language and it can be transferred and communicated in a formal, systematic and structured manner, such as organizational procedures, rules, scientific equations, manuals, etc. Compared with explicit knowledge, tacit knowledge is an unconventional form of knowledge, so it is not perceivable. Tacit knowledge is personal knowledge. It is rooted in actions, procedures, commitments, values, and emotions. In other words, special experience is needed in order to communicate tacit knowledge through observation and imitation. Drucker believes that tacit knowledge cannot be explained by words, and can only be demonstrated to prove that it exists. The only way to learn tacit knowledge is to comprehend and practice [6]. He also believes that tacit knowledge is derived from experience and skills and must be acquired through practice.

According to the literature research, tacit knowledge has the following characteristics:

1. The individuality and embodiment of tacit knowledge

Tacit knowledge has characteristics unique to individuals [7], cannot be used to communicate with others, and is embedded in personal behavior in special situations. Nonaka and his colleague believe that tacit knowledge is a form of personal knowledge [8].

2. The tacitness of tacit knowledge

Tacit knowledge is closely related to actions. For example, apprentices can only rely on practice to explore the master's operating know-how and experience. Technological tacit knowledge is created through personal behavior and direct experience "here and now" [9]. Tacit knowledge is a process of intelligence and cognition. It can neither be expressed nor publicly shown, but it can be implied or simply understood. Specifically, work involving highly tacit knowledge tends to involve practical, action-oriented know-how that is difficult to articulate, that is acquired only through personal experience, and is seldom expressed openly [10].

3. The empirical nature of tacit knowledge

Tacit knowledge is a term referring to knowledge gained based on experience, characterized by the fact that it is not formal and is process-based in nature [11]. Tacit knowledge is created in experience and stored in the form of individual ability. Although tacit knowledge is past experience, unconscious application of tacit knowledge by the individual does not require long-term thinking. In the context of emerging public health incidents, tacit knowledge as individual's past experience has a wide-ranging impact for building resilient and responsive health systems [12]. Since tacit knowledge is obtained through practical experience and observation in various environments, it is often called empirical knowledge.

4. The difficulties in spreading and sharing tacit knowledge

Tacit knowledge is difficult to obtain, transfer, share and manage. An incentive mechanism can make the enterprise employees share their inner individual tacit knowledge, which in turn, makes the shared knowledge explicit, transfers the explicit knowledge into assets, and finally translates the asset knowledge into incomes [13]. In practice, tacit knowledge sharing between employees is rare, firms should employ various methods to facilitate the intrinsic motivations to promote sharing [14]. Tacit knowledge is not only the most difficult to share and keep in organizations, but also rightly perceived to be the most valuable knowledge asset owing to its contextualized and experience-based nature [15].

5. The monopolization of tacit knowledge

The monopoly of tacit knowledge is evident in that it is obtained not through words, images or other knowledge [16]. It is accumulated in long-term practice by individuals who have invested time, experience, material, etc. Therefore, tacit knowledge has value, the individuals within an organization may have a strong monopoly on some kinds of rarer tacit knowledge [17], especially when monopoly knowledge can bring core competitiveness and additional economic returns, the same is true for organizations with tacit knowledge.

The influence of tacit knowledge on the core competitiveness of organizational development

In the field of economics and management, research on the interconnection between tacit knowledge and the core competitiveness of organization has also attracted widespread attention of scholars. Lubit proposed the importance of tacit knowledge in enterprises, and believed that the competitive advantage of enterprises does not come from resources and markets but from the tacit knowledge of enterprises [18]. The importance of tacit knowledge has been pointed out in relation to decision-making, time-management, quality and competitiveness in organizations. Tacit knowledge is the most strategically important resource of an organization [19]. Okuyama believes that tacit knowledge plays an important role in incremental innovation through the study of drug discovery cases, and companies should pay more attention to the contribution of tacit knowledge in problem solving related to incremental innovation [20]. Many studies have shown that when explicit knowledge is identified by other competitors, an organization can only gain its competitive advantage by evaluating its tacit knowledge. The organizations should be conscious about the importance of the tacit knowledge the employee possesses for the development of the organizations [21]. In his book, Nonaka described in details the importance of tacit knowledge for the company's success [22]. He believes that in a dynamic and rapidly changing environment, the ability of an enterprise to gain a competitive advantage depends on its ability to continuously examine various factors in its internal and external environments. The only way to do this is to focus on the knowledge created by the individuals in the organization. Knowledge creation leads to continuous innovation, and continuous innovation brings competitive advantages. The creation and conversion of organizational knowledge becomes a necessary condition for the survival and development of enterprises. Therefore, Nonaka proposed a SECI model, the core content of which is how companies can establish an organization based on knowledge innovation through the process of mutual conversion between tacit knowledge and explicit knowledge. This article focuses on the conversion process of externalization. The externalization process is mainly the explicit description of tacit knowledge and conversion of it into an easy-to-understand form. Through metaphors, analogies, diagrams, concepts and models, the tacit knowledge that can be made explicit is clearly expressed in concepts, etc., so as to implement the conversion of tacit knowledge into explicit knowledge. Externalization is an important way to expand the scope of tacit knowledge flow and conversion, as well as to realize enterprise knowledge creation.

Implementation of tacit-to-explicit knowledge conversion

By developing a semantic web platform, it can capture the domain experts' tacit knowledge and allow collaboratively annotating experts' knowledge in a computer interpretable format to form common explicit knowledge that can be shared and reused by human and machines [23]. Olaisen and Oivind conducted a longitudinal survey study of two teams of staff employed with a Norwegian manufacturer. Through rotating role mechanism and socialization process they successfully encouraged the team members to convert their tacit knowledge into collective explicit knowledge, and the innovation results have been achieved within a certain period of time. The authors prove that the conversion of tacit knowledge into explicit knowledge helps increase efficiency and effectiveness in knowledge-intensive corporations [24]. Some scholars had proposed to build a knowledge base to replace human expert query system with the use of intelligent search technologies and chatbots, thereby increasing the efficiency of tacit knowledge externalization [25].

Knowledge management and game theory

Game theory was proposed by Von Neumann and Morgenstern in 1944. It mainly studies the game subject behavior, i.e., how each subject selects strategies to maximize its utility and an effective way to reach equilibrium [26]. Game theory is the method of studying the phenomenon of struggle or competition, and it is widely used in biology, economics, international relations, computer and political science, military strategy and in many other disciplines. The research method of game theory is to abstract basic elements from complex phenomena, analyze the mathematical model composed of these elements, and then gradually introduce other factors that influence the development of this phenomenon for reanalysis, and finally obtain the corresponding research results. In the application of knowledge management, Jiang and Xu established a nonlinear evolutionary dynamic game model to explore the impact of structural changes on the tacit knowledge sharing behavior of IT R&D team. They believe that managers can only strengthen the reward system or reduce sharing costs, and only when a certain critical threshold is reached, the effectiveness of knowledge sharing will be significantly improved [27]. Li set up a dynamic cooperative game model to reveal the strategic characteristics of knowledge sharing between knowledge transferors and knowledge recipients, and evaluates the role of institutional constraints and incentives in promoting knowledge sharing [28]. Qin and Wang regard the organization as a system, applying the multi-agent systems to consider the games among individuals and between the individuals and the organization based on their different payoffs, and explain the tacit knowledge sharing mechanism between individuals and organization. They believe that individual tacit knowledge can be converted into an organization's explicit knowledge through socialization and effective integration, and some can be converted into individual tacit knowledge, and eventually, forms organizational culture [29]. Based on the constituent elements of the psychological contract when members participate in knowledge collaboration, some scholars use game theory to establish a cost game model and profit-sharing game model for practical knowledge collaboration [30].

Game Model of the Externalization

According to the characteristics of tacit knowledge, the process of externalization is not necessarily sufficient, which will ultimately affect the efficiency of knowledge creation in the organization. Members of the organization choose confrontation or cooperation in the conversion of tacit knowledge depending on whether the interests of all participants are consistent. This article suggests that it is necessary to establish an effective incentive mechanism from the perspective of game theory to take advantage of the tacit knowledge of organization members.

Organization \ Employee	Positive	Negative
Incentive	*Payoffs of organization:* $(1-\alpha)\ i_pV-W$ *Payoffs of employee:* αi_pV+W-C	*Payoffs of organization:* $(1-\alpha)\ i_nV-W$ *Payoffs of employee:* αi_nV+W
Non-incentive	*Payoffs of organization:* i_pV-W *Payoffs of employee:* $W-C$	*Payoffs of organization:* i_nV-W *Payoffs of employee:* W

Fig. 1. Game Matrix of Externalization within organization

Due to the fact that the knowledge of employees in the organization is inseparable from them, and most of it is invisible and uncoded personal knowledge, experience and skills are accumulated by employees in long-term work practices. If their tacit knowledge can successfully be converted into explicit knowledge of the organization through externalization, it can increase the overall knowledge stock of the organization, and then enable the organization to obtain continuous innovation capabilities and competitive advantages. Therefore, the smooth conversion of employees' personal tacit knowledge into the organization's explicit knowledge is the key to the improvement of organizational knowledge stock, which in its turn depends on the aspiration of employees. Through the dynamic game analysis between the organization and its employees, this paper establishes a dynamic analysis model and incentive factor based on employee incentive and restraint mechanisms as shown in the Fig. 1. The two players of the game are: organization and employee. There is information asymmetry between the two parties, and the employee is the player which captures the information advantage; the employee's actions are based on the organizational behavior; the organization has two strategies in terms of employees' aspiration to convert knowledge: incentive and non-incentive strategies; according to the organization's strategy, employees can choose one out of two strategies, namely, positive or negative conversion of tacit knowledge.

i_n and i_p — the probabilities of converting tacit knowledge when employees are negative and positive, $0 \le i_n < i_p \le 1$;

C — the cost of employees converting tacit knowledge, $C > 0$;

V — the value created by employees for the organization after their own tacit knowledge is externalized, $V > 0$;

α — the incentive factor when the organization motivates employees, i.e., a part of the value V created by employees for the organization, $0 < \alpha < 1$;

W — the basic income of employee.

When the organization's strategy is non-incentive, because $W - C < W$ is constant, employee will choose to be negative at this time, and the final equilibrium is non-incentive, negative. It is an inefficient Nash equilibrium.

When the organization's strategy is incentive, whether employee will positively convert tacit knowledge depends on the size of his or her own benefits: if $\alpha i_pV + W - C > \alpha i_nV + W$, employee will choose to be positive, and the equilibrium is incentive, positive. It is an ideal Nash equilibrium. If $\alpha i_pV + W - C < \alpha i_nV + W$, employee will not positively convert tacit knowledge even under incentive conditions. At this time, the equilibrium is incentive, negative, which is also an inefficient Nash equilibrium. In this model, the game between the organization and employee is regarded as one game behavior. The game between the two players should be a continuously repeated process.

Assume that the decision and behavior of the organization and employee are to maximize the sum of the present value of their future payoffs. The payoffs of the two players not only depend on how to allocate the value created by the employees for the organization in the current period, but is also related to the existing knowledge stock accumulated by the employee through the conversion of tacit knowledge in the early stage, the knowledge stock consists of the knowledge, skills, and abilities of employees [31]. The more positive the conversion in the early stage is, the larger the accumulated knowledge stock will be, and the more value is created for the organization in this period of time.

The following notations have been added to the new repeated dynamic model:

n — the expected working time of the employee in organization;

r_t — the current discount factor;

Q_t — the current explicit knowledge stock;

V_t — the current value created by employee in converting own tacit knowledge;

E_t — the current positive degree of employee in converting tacit knowledge;

θ_t — the contribution coefficient of the organization's explicit knowledge stock to the current payoffs;

Ω — the employee's opportunity cost of working in the enterprise, which is equivalent to the employee's social average personal income;

C_t — the current cost of converting tacit knowledge by employee;

φ — the employee's degree of risk aversion (risk tolerance), $\varphi > 0$;

ω^2 — the variance of the benefits obtained by the organization using new explicit knowledge.

In long-term cooperation, the objective function of the organization related to maximization of the payoffs by determining the basic income of employee W and the incentive factor α is:

$$\max \sum_{t=0}^{n} r_t \left[(1-a)\Big(V_t\big(E_t(\alpha)\big) + \theta_t Q_t\big(E_{t-1}(\alpha)\big)\Big) - W \right]. \tag{1}$$

In long-term cooperation, the employee takes appropriate actions according to the incentive factor α to achieve the objective function of maximizing payoffs:

$$\max \sum_{t=0}^{n} r_t \left[\alpha V_t\Big(E_t(\alpha) + \theta_t Q_t\big(E_{t-1}(\alpha)\big)\Big) + W - \frac{1}{2}\alpha E_t^2 - \frac{1}{2}\varphi\alpha^2\omega^2 \right]. \tag{2}$$

The constraint condition for employee to participate in this game is:

$$\max \sum_{t=0}^{n} r_t \left[\alpha V_t\Big(E_t(\alpha) + \theta_t Q_t\big(E_{t-1}(\alpha)\big)\Big) + W - \frac{1}{2}\alpha E_t^2 - \frac{1}{2}\varphi\alpha^2\omega^2 \right] \ge \sum_{t=0}^{n} r_t \Omega. \tag{3}$$

The incentive constraint condition for employee to participate in this game is:

$$E_t(\alpha) = \frac{\alpha}{C_t}. \tag{4}$$

Substituting (3) (4) into (1), and then seeking the first derivative of α, the optimal solution is:

$$\alpha^* = \frac{\sum_{t=0}^{n} r_t \left(V_t' + \theta_t Q_t'\right)}{\sum_{t=0}^{n} r_t \left(1 + \varphi C_t \omega^2\right)} > 0.$$

The results of research and their discussion

In this Nash equilibrium state, the incentive factor α is an increasing function of the accumulated amount of explicit knowledge of the previous organization Q, its influence coefficient on organizational revenue θ, and the marginal revenue V of the organization generated by the employee's marginal conversion of tacit knowledge. In other words, the level of incentives for employee in each period is positively correlated with θ and V. When the marginal payoffs of the organization generated by the positive conversion of the employee marginal conversion of tacit knowledge rises, the payoffs of the organization also increase. In order to further motivate the employee to positively convert tacit knowledge, the organization will increase the incentive factor α, accordingly, the payoffs of the employee will also grow, thus forming a virtuous circle. In addition, the positive conversion of tacit knowledge by employees will increase the quantity and quality of the organization's knowledge stock, which will affect the organization's subsequent competitiveness. The level of incentive factor α stipulated by the organization will change the quantity and quality of the organization's knowledge stock by influencing employees' enthusiasm, and will ultimately affect its long-term operating activities. This shows that the incentives for employees should not only be linked to the actual payoffs of the organization in the current period, but also should be linked to the increase in the quantity and quality of knowledge stock within the organization.

At the same time, the incentive factor α is a decreasing function of the employee's risk aversion degree φ, the cost of converting tacit knowledge C, and the variance of the benefits obtained by the organization using new explicit knowledge ω^2. For employees, when the process of converting tacit knowledge is more difficult, the uncertainty of the additional income brought by the conversion process is greater, and the risk aversion degree of employees is higher, they are willing to take less risks. This means that employees will require higher risk-free income when signing an incentive contract with the organization, but due to the fact that organization is at an information disadvantage position concerning the cognition of tacit knowledge, and the influence of explicit knowledge generated by externalization on the profit of the organization needs to be verified by time, organization can truly understand its value only after the application of new explicit knowledge. It is unfair for organization to pay high risk-free income to employees from the beginning. This phenomenon shows that it is difficult to reach an effective incentive contract between the organization and employees at this time. Therefore, an effective incentive mechanism design should not only connect employees' income with the organization's new benefits, but should also consider such factors as employees' risk tolerance and costs.

Conclusion

Based on the above analytical results of the tacit knowledge conversion game, managers can take a set of effective incentive measures to ensure the smooth progress of tacit knowledge conversion.

1. Developing salary payment mechanism based on knowledge conversion contribution. The system refers to linking the knowledge achievements that can determine the benefits in a short time with the current income of the employees, and can motivate the employees through the issuance of salary and provision of bonuses. It is also possible to link the long-term income of employees with knowledge achievements that are difficult to determine and are mainly realized in a long-term period, and to motivate the employees by giving stock rights and options to achieve the effect of extrinsic motivation.

2. Developing position promotion mechanism based on knowledge conversion contribution. The promotion system means that employees who have not only achieved beneficial knowledge results, but also have management capabilities, and are loyal to the organization can be motivated by promotion methods. Employees who attach importance to fame can be motivated by the method of knowledge signature. For example, a particular technology or marketing knowledge can be named after an employee in order to inspire him/her. Employees can also be sent to high-level research institutes and universities for undergoing knowledge training. Through these methods, the effect of intrinsic motivation to employees can be achieved.

Tacit knowledge always exists depending on the subject of knowledge, and the subject's willingness determines the efficiency and results of tacit knowledge sharing and conversion. An effective incentive mechanism is the driving force for the flow of sharing and conversion of tacit knowledge within the organization. Based on the analysis of the repeated dynamic game model of externalization by the SECI model, this paper establishes the incentive factor, and proposes corresponding incentive mechanisms from the perspective of intrinsic and extrinsic motivation. It is aimed at eliminating obstacles in the process of tacit knowledge sharing and conversion among employees, maximizing personal and organizational benefits, providing guarantees for the organization's innovation and sustainable development, as well as at consolidating the core competitiveness of the organization on the basis of effective management of tacit knowledge.

Directions for further research

Due to the many different working groups in the organization, the authors will further use the evolutionary game theory to examine the behavior of tacit knowledge sharing between different groups in the framework of the dynamic process. The good tacit knowledge sharing within the organization (i.e., the SECI model socialization process) is a prerequisite for further conversion of tacit knowledge into explicit knowledge. The evolutionary game theory is based on the new theory of biological evolution, and its basic content is that in a group of certain size the players are constantly engaged in repeated gaming activities. Because of the presence of limited rationality, the players cannot find the best equilibrium point in each game, so the best strategy is to imitate and improve the optimal strategy of itself and of others. Through this long-term imitation and improvement, all players will tend to achieve a stable strategy balance. With the help of evolutionary game theory, we can identify the reasons which affect strategical evolution during the tacit knowledge sharing process within the organization, and continuously improve the systemic incentive mechanism for organizational members.

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